PB84-155225

Geotechnical Quality Assurance of Construction of Disposal Facilities

(U.S.) Army Engineer Waterways Experiment
Station, Vicksburg, MS

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Feb 84

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA-600/2-84-040
February 1984

PB84-155225

GEOTECHNICAL QUALITY ASSURANCE OF CONSTRUCTION OF DISPOSAL FACILITIES

by

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Interagency Agreement No. AD-96-F-2-A077

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/2-84-040

2.

3. RECIPIENT'S ACCESSION NO.
PB84 155225

4. TITLE AND SUBTITLE
GEOTECHNICAL QUALITY ASSURANCE OF CONSTRUCTION
OF DISPOSAL FACILITIES

5. REPORT DATE
February 1984

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
S. J. Spigolon and M. F. Kelley

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Geotechnical Laboratory
U.S. Army Engineer Waterways Experiment Station
Box 631
Vicksburg, MS 39180

10. PROGRAM ELEMENT NO.
BRD1A

11. CONTRACT/GRANT NO.
AD-96-F-2-A077

12. SPONSORING AGENCY NAME AND ADDRESS
Municipal Environmental Research Laboratory-Cin.,OH
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

13. TYPE OF REPORT AND PERIOD COVERED
Final 4/82 - 12/82

14. SPONSORING AGENCY CODE
EPA/600/14

15. SUPPLEMENTARY NOTES
Contact Project Officer: Robert E. Landreth 513/684-7871

16. ABSTRACT

This report presents four major topics related to the permittee's responsibilities during construction, operation, and closure of a hazardous waste disposal facility: (1) geotechnical parameters that should be tested and/or observed, (2) selection of sampling methods and sample sizes for the geotechnical parameters, (3) laboratory and field testing methods for investigating geotechnical parameters, and (4) a quality assurance program suited to the unique responsibilities of the permittee.

The purpose of the report is to provide technical background for use by permittees, designers, specifiers, quality assurance engineers, and permit writers for hazardous waste disposal facilities. The document addresses the quality control aspects of construction, operation, and closure of a hazardous waste disposal facility (it is assumed that the quality aspects of site selection, characterization, and design have already been managed). Types of facilities covered by the report include landfills, surface impoundments, waste piles, and land treatment units.

This report was submitted in fulfillment of Interagency Agreement No. AD-96-F-2-A077 by the U.S. Army Waterways Experiment Station in cooperation with the U.S. Environmental Protection Agency. The report covers the period April to December 1982, when work was completed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT
RELEASE TO PUBLIC

19. SECURITY CLASS (This Report)
UNCLASSIFIED

20. SECURITY CLASS (This page)
UNCLASSIFIED

21. NO. OF PAGES
192

22. PRICE

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement number AD-96-F-2-A077 to the U.S. Army Engineer Waterways Experiment Station. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

The protection of human health and the environment requires that research be conducted to determine the manner in which hazardous waste disposal facilities should be constructed. This study is intended to provide technical background on hazardous waste disposal facility construction for use by designers, specifiers, quality assurance engineers and permit writers. The study addresses the subject of quality assurance of site geotechnical parameters during the construction, operation, and closure of landfills, surface impoundments, waste piles, and land treatment units.

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Laboratory

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ACKNOWLEDGMENTS

This report was prepared by the Geotechnical Laboratory (GL) of the U.S. Army Engineer Waterways Experiment Station (WES). The authors of the report were Dr. S. J. Spigolon and CPT M. F. Kelley. Investigation team members providing technical advice were H. V. Johnson, Jr., and P. G. Tucker. The work was conducted under the direct supervision of G. B. Mitchell, Chief, Engineering Group, Soil Mechanics Division, GL, and the general supervision of C. L. McAnear, Chief, Soil Mechanics Division, GL, and Dr. W. F. Marcuson, III, Chief, GL. COL Tilford C. Creel was Commander and Director of WES during preparation of this report. Mr. Fred R. Brown was the Technical Director.

SECTION 1

INTRODUCTION

The U.S. Environmental Protection Agency (EPA) issued its interim final rules and regulations for hazardous waste disposal facilities in the Federal Register, on July 26, 1982 (E.P.A., 1982). As stated in the preamble, "EPA wants to make sure that the issuance of a RCRA (Resource Conservation and Recovery Act) permit for a facility means that a certain level of protection is provided and that the public can be assured* that the prescribed level of protection will be achieved."

Also in the preamble, "Section 3004 of RCRA provides that EPA has authority to issue regulations covering owners or operators of (hazardous waste) treatment, storage and disposal facilities as may be necessary to protect human health and the environment." Given this authority, the EPA has charted a defense strategy with two basic elements. The "first line of defense" calls for facility design and operating standards that prevent groundwater contamination by controlling the source of contamination. The "second line of defense" is a groundwater monitoring and response program designed to remove leachate from the groundwater if it is detected.

The EPA believes that adequate protection will be afforded if hazardous waste disposal facilities meet both (a) the technical performance standards and (b) the environmental performance standards promulgated to execute their two element defense strategy. A quality assurance program for the construction, operation, and closure of a hazardous waste disposal facility, though not required by the current regulations, is mandated in EPA policy and is a management practice which can assure that these standards are met, that the strategy is executed, and that human health and the environment are protected.

THE TOTAL QUALITY SYSTEM

Quality is defined (Lester, Enrick and Mattley, 1977) as the level of performance of a material, product, or process, measured in terms of specified requirements. In construction, the total quality system, as described by Abdun-Nur (1963), Willenbrock (1976), and others, contains several subsystems: Planning, Design, Plans and Specifications, Construction, and Monitoring. The purpose of these activities is to insure that quality is what it should be.

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* Underline emphasis is that of the authors.

Planning establishes the quality level that is desired. For a disposal facility, planning begins with the Environmental Protection Agency. The agency interprets the needs of society and promulgates rules and regulations. These rules and regulations establish levels of quality that the EPA recognizes as necessary and sufficient to protect the human health and environment.

In the design subsystem, an analysis is made of available resources. The desired quality levels are fixed in terms of what is to be required at the specific site, based on site characterization and other studies.

In the plans and specifications subsystem, the requirements of the design are translated into specific instructions for achieving the required quality levels. Methods for evaluating the quality of construction, and the acceptable level of quality as defined by these methods are integral parts of the specifications.

The construction subsystem for a disposal facility includes initial construction, operation, and closure. Construction transforms the designed facility into reality, and quality becomes physically real. Quality assurance activities within the construction subsystem include (a) process control and (b) acceptance sampling and testing. (See Construction Quality Assurance, later in this section.)

Finally, monitoring of the behavior of the completed disposal facility should provide data of how the facility actually performs. By closing the quality loops, monitored performance data can be used by EPA in the planning stage of future projects to review its desired, and mandated, quality levels.

PURPOSE OF REPORT

This study report is intended to provide technical background for use by designers, specifiers, quality assurance engineers, and permit writers. It is directed only to that part of the total quality system (Abdun-Nur, 1963) that encompasses quality assurance during the construction, operation, and closure of a hazardous waste disposal facility. This report does not address the design of a hazardous waste disposal facility. Hence, no guidance for the quality levels of disposal facility site selection, site characterization or design is included in the report.

The technical background presented in this report is aimed at the permitting requirements that deal with quality assurance. It specifically treats the subject of quality assurance of site geotechnical parameters during construction, operation, and closure of:

a. Landfills (burial sites)

b. Surface impoundments

c. Waste piles

d. Land treatment units

It does not address injection wells or seepage facilities.

This report is not intended to be a textbook that teaches the fundamentals of soil mechanics, soils testing, or statistical methods to those engineers responsible for the geotechnical design and/or construction of a disposal facility. Rather, this report should provide both specialists and nonspecialists involved in the design or evaluation of design (permit review) with a common basis for understanding of the topics discussed. The information provided summarizes each topic, presents the most pertinent features of each, and provides terminology, definitions, equations, applications, and literature references. For further study, or to acquire an in-depth understanding of the various topics, the reader is referred to the several textbooks on each topic.

SCOPE OF THE REPORT

During the construction, operation, and closure of a hazardous waste disposal facility, the permittee (owner or operator) has the responsibility to test and/or observe and to document:

a. The verification of (a) geologic media site characterization and (b) soil engineering properties design assumptions following the exposure of trench or impoundment walls and bottoms

b. The quality of geotechnical construction, involving materials and workmanship, for compliance with specification and permit requirements

This document discusses four major topics related to the geotechnical quality assurance responsibilities of the permittee during the construction, operation, and closure of a disposal facility:

a. In Section 2, those geotechnical parameters that should be tested and/or observed and documented are identified and described. The reasoning for their selection is given. Tests and/or observations used for construction process control are often different than those used for site media verification or for acceptance evaluations.

b. In Section 3, sampling and frequency of testing for the geotechnical parameters are discussed. The discussion is based on statistical methodology and includes sampling plans, selection of sample size, and calibration of test equipment.

c. In Section 4, the commonly used laboratory and field testing and/or observation methods, needed for investigation of the geotechnical parameters defined in Section 2, are identified and described. A discussion of merits and limitations of the various methods is given. Criteria are proposed for selection among alternative test methods.

d. In Section 5, a quality assurance program, suited to the unique construction responsibilities of the permittee, is presented and discussed. The documentation necessary to provide a valid record of the quality of the work is recommended.

The report is limited to consideration of geotechnical tests and/or observations, i.e., involving physical properties of soils. Geochemical and geohydrologic tests such as soil pH, ion exchange capacity, pore water age, or infiltration capacity, are not included. It is uncommon in the earthwork construction industry to perform geochemical or geohydrologic tests as part of quality control of construction. But if such tests are deemed necessary by the permittee's forces during construction, they certainly should be performed on an as-needed basis. An example is the need to verify an engineering property assumption made during the design stage on the existing soils in a newly accessible part of the site.

Although this report is restricted to geotechnical parameters, most of the concepts of sampling inspection, quality control, and documentation apply equally well to site characterization studies, geochemical or geohydrologic studies, monitoring, and other site activities not addressed.

CONSTRUCTION QUALITY ASSURANCE

Willenbrock and Shepard (1980) have compared Quality Assurance/Quality Control (QA/QC) Systems within the civilian construction industry. Included are (a) highway construction, (b) nuclear power plant construction, (c) U. S. Navy and U. S. Army Corps of Engineers facilities construction, and (d) building construction by private or public owners. In most areas of construction, including highway, Navy, Army, and buildings, there is a contractual relationship between the owner (whether public or private) and the contractor. The owner's design representative prepares plans and specifications. The contractor is expected to use those control of quality, or process control, procedures that are necessary to control his materials and workmanship to comply with the plans and specifications. The owner's inspectors perform those acceptance sampling and testing functions needed to give confidence to the owner that the materials provided and the work performed are acceptable. Thus three distinct quality groups, responsibilities, and procedures, result in a near adversary relationship between the owner and the contractor.

This near adversary relationship can be illustrated by typical earthwork specifications (Soil Conservation Service, 1973) which state, "These tests performed by the Engineer will be used to verify that the fills conform to the requirements of the specifications. Such tests are not intended to provide the Contractor with the information required by him for the proper execution of the work and their performance shall not relieve the Contractor of the necessity to perform tests for that purpose."

EPA policy creates a unique construction situation by vesting the responsibility for all aspects of quality assurance with the permittee (EPA, 1982). This is similar to the policy of the U. S. Nuclear Regulatory Commission as given in 10 CFR 61.12 (NRC, 1982). The NRC applies this policy to the licensee for nuclear power plant construction and to the licensee of a low-level radioactive waste disposal site. However, the major turnkey contractor for a nuclear power plant must deal with numerous subcontractors and materials suppliers, thereby creating the same near adversary situation as in other civilian construction.

The permittee of a hazardous waste disposal facility is therefore somewhat unique in the construction industry in that he is totally responsible, to the regulatory agency, for the facility's (a) site selection, characterization, and design, (b) construction, operations, and closure, and (c) quality assurance activities, including process control, acceptance sampling and testing, and documentation of the quality assurance program. That he is responsible for both construction and its inspection poses a potential conflict of interest. The quality assurance program presented in Section 5 of this report accounts for the permittee's unique situation and this potential conflict of interest.

During the life of a disposal facility, the permittee will have three major functions within his construction responsibilities:

a. The Design Function: This function includes all pre-permit activity, such as site selection, site characterization, analysis and design, plans and specifications, and preparation of the permit application. Post-permit activities include verification of design conditions for exposed site media (see Figure 1) and critical evaluation of inspection reports.

b. The Construction and Operations Function: This function includes provision of all materials (including off-site materials) and workmanship during construction; i.e. to include all materials and workmanship involved in site preparation, trench excavation, and the placement of liners, embankments, leachate collection systems, intermediate covers, and final covers.

c. The Inspection Function: This function includes the sampling, testing and/or observation, initiation of corrective action for instances of non-acceptance, and documentation of all the post-permit construction work. The inspection function involves all the materials provided by, and all the workmanship of, the permittee as part of his construction and operations function.

Discussion of the organizational structure by which the permittee may accomplish these functions is contained in Section 5 of this report. The permittee may use in-house forces or external contract forces, or any combination of the two. It is inevitable that the permittee's forces responsible for the design and inspection functions will have different attitudes, concerns, and responsibilities than the forces responsible for the construction and operations function. Therefore, it is essential that each of these separate forces report directly to the permittee's top level management rather than for any one group to be subordinate to another.

It is the permittee's inspection function that is of particular concern. Unlike other parts of the construction industry, the permittee of a hazardous waste disposal facility is responsible for both construction process control and owner acceptance sampling and testing. During construction the permittee

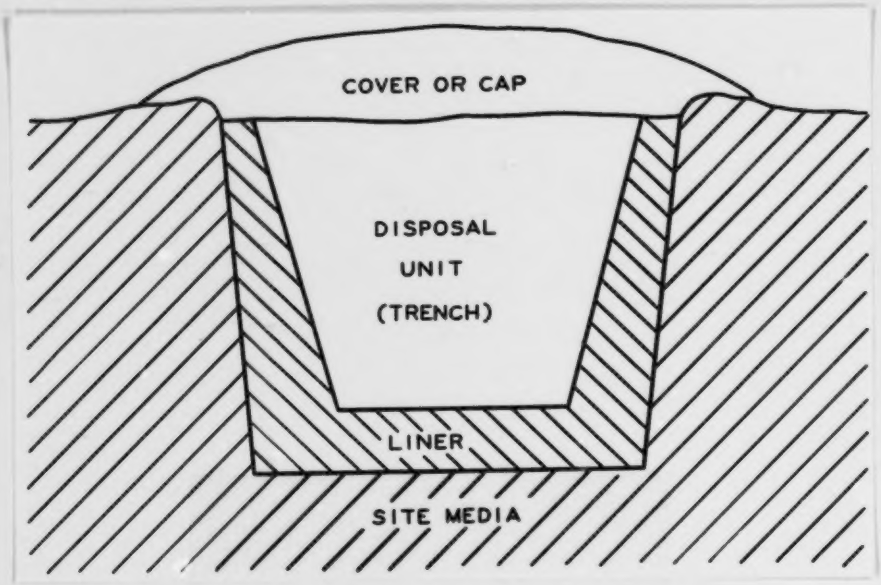

Figure 1. Relationship between site media and disposal unit at disposal facility

can fulfill these two responsibilities synergistically. That is, the feedback from observations and from acceptance sampling and testing can frequently be used to control the construction process to provide the specified level of quality by indicating the corrective measures to be taken.

Although the permit requirements and the construction specifications, prepared as part of the permittee's design function, will normally specify performance or end-result standards, the permittee's process control of his men, machinery, and materials will more likely be by method, or recipe, specifications.

Because of the somewhat unique permittee-regulatory agency relationship, the need for complete inspection documentation is critical. This need includes not only the documentation of acceptance tests and observations made to establish compliance with the specifications, but also (a) the verification of geologic media site characterization and engineering soils properties design assumptions following the exposure of walls and bottoms of disposal units, and (b) observations and tests made as part of the permittee's process control of materials and workmanship. Critical interpretation of the observations and tests by competent, knowledgeable, experienced and qualified personnel, responsible to the permittee, is also essential. This complete recording, review, and acceptance of inspection observations and tests will then serve (a) to provide the regulatory agency with confidence in the quality assurance program, and (b) to provide a basis-in-fact in the event of future problems and/or litigation.

SECTION 2

GEOTECHNICAL PARAMETERS

The permittee is responsible for the quality of all geotechnical materials and workmanship during the active life of a disposal facility. This life includes (a) the pre-permit stage: site characterization, analysis, design, and specification, and (b) the post-permit stage: construction, operation, and closure. The geotechnical engineering aspects of both phases require data on the engineering properties of those parts of the soil and rock formations of the site that influence the project.

The materials to be characterized by engineering properties include:

a. Site media (See Figure 1)

    (1) In situ materials, not moved or disturbed

    (2) Excavated, transported, manipulated, and processed materials

b. Off-site materials

    (1) Nearby natural materials, such as sand from a nearby borrow pit

    (2) Imported or shipped natural materials, such as bentonite clay

    (3) Imported or shipped manufactured materials, including geomembranes, geotextiles, portland cement, and asphalt cement

During the design phase of a disposal facility project, all of the existing or proposed materials are characterized by their location, dimensions, and engineering properties. Tests for the engineering properties are difficult and time consuming. Therefore, during construction the QA inspector usually uses simpler, more rapidly performed soil tests that are good indicators of the engineering properties in his acceptance evaluation.

The construction process involves control of materials and workmanship. Materials are tested and/or observed for use in the project prior to their incorporation. Then construction workmanship is used to process the materials to their final form. The workmen, their supervisors, and the process inspector must interact to properly control the process. The tests and/or observations used to control the process may be one or more of the acceptance tests, or may be any other test/observation that will directly inform the workman and/or his immediate supervisor of the necessity for corrective action. The objective of process control is to direct the work in an efficient manner, to catch mistakes before or as they occur, to cause the mistakes to be corrected, and to ultimately produce an acceptable product. The project specifications usually state only the acceptance/rejection standards.

As an example, the design may require that a clay liner material be compacted so that a given level of imperviousness (low permeability) is achieved throughout the entire liner. The required level of permeability is defined. For field use, this is translated into a specified density and water content. These are usually related to a laboratory compaction test that adjusts the density and water content requirements for changes in soil texture. Acceptance levels are set based on field density and water content tests. The workman, on the other hand, can control only his processing. Given an acceptable soil, he and the process control inspector can control lift thickness, uniformity of lift thickness, water content (by additional water or by drying), type and size of roller, number of passes, and uniformity of rolling. They must then translate these factors into a pattern of work that will result in acceptable soil density and soil water content which will indicate that the required low permeability is achieved.

The objective of this section of the report is to identify those geotechnical parameters that should be observed or tested and documented during the construction, operation, and closure of a disposal facility. These are parameters defined in project specifications for the evaluation and acceptance of the work. In many instances these will be the same parameters as those used in the pre-permit stage. Therefore a brief discussion of the pre-permit stage will introduce the parameters.

PRE-PERMIT STAGE

The investigation of a proposed disposal facility includes geologic studies, geohydrologic studies, drainage studies, site investigation by geophysical and test drilling methods, and the sampling and testing of the site media. Specific details of the techniques for these studies are beyond the scope of this report. It is assumed that the permittee, in performing his design function, will employ qualified professionals to perform and evaluate the work in accordance with established, rational practices. The combination of subjective geologic studies and geotechnical engineering site investigations should result in adequate data for the purpose of site characterization for design.

Geology and Geohydrology

Site characterization studies start with inferences based on site geologic studies. The existing geologic information on the site area is reviewed. Studies may include earth satellite photograph interpretation, aerial photograph interpretation, and field studies including observation of terrain, natural and man-made cuts, and drainage. Erodibility potential may be included in the studies. They are expected to provide evaluations of:

a. Stratigraphy: The origin of each stratum and its relationship to adjacent geologic units is inferred. Subsurface irregularities or a pattern of spatial variation in quality characteristics may be revealed.

b. Lithology: The soil and rock strata should be characterized on the basis of mineralogy, texture, fabric, and origin of materials.

c. Structure: Macro(gross)-structure includes bedding attitudes as well as fracture systems. The latter include faults, cracks, joints, and slickensides.

d. Ground Water: The presence of aquifers and perched water tables, including their flow gradients, flow direction, and recharge and discharge areas, should be defined. Surface drainage should be established as it affects the disposal site drainage.

Site Investigation

The subsurface investigation of the immediate site may use geophysical methods and drilling and sampling. The objective is to define material types and engineering properties, material zone boundaries, and the spatial and random variability of engineering properties in each material and zone. Material variability is discussed in detail in Section 3 of this report.

Material type and variability are best established by soil index properties tests on samples from drill holes and test pits. These tests are relatively inexpensive and easily performed. The drill holes and/or test pits should be located through a combination of geologic inference and the sampling methods of Section 3. In this manner, random samples of each stratum can be used to characterize the classification and variability of the various strata.

Tests for engineering properties require high quality undisturbed samples (ASTM, 1970). Construction experience has shown that only few projects can afford the expense of large numbers of such samples and tests. Therefore, only a sufficient number of engineering properties tests are made, with associated index properties tests, to confirm the expected relationships between the two and to supplement geologic inferences about the soil engineering properties. This information is extrapolated over the site by means of the data from the more numerous index properties tests.

The accuracy of the determination of material zone boundaries and the location of a water table is a function of the number and quality of borings made. These borings can often be supplemented by geophysical tests which cover wide areas less expensively than drilling. Thin or discontinuous zones are easily missed and the interpretations of layer thicknesses are sometimes affected by the vertical interval between samples. Within the upper 10 to 15 feet of the ground surface, test pits can disclose the total soil profile over a limited area (i.e. the walls of the pits).

ENGINEERING PROPERTIES TESTS

During the analysis and design phase of the pre-permit stage, the permittee makes estimates of the configuration and engineering properties of the natural site media. These are based on the geologic and site investigation studies referred to above. The permittee also makes assumptions about the expected engineering properties of the construction placed materials. This requires quantitative and specific information on the physical and strength properties of soils that have direct and valid application to the design problem (ASTM, 1970). These properties include permeability, compressibility, and shear strength (USAE, WES, Appendix A, 1960). Although not considered an engineering property, the susceptibility of the site soils to erosion (erodibility) by water or air should be estimated in the design phase.

Permeability

The permeability of a soil or other material is a major influence on the flow of water or other fluids through liners, covers, and leachate collectors. It also affects the time rate of settlement and the rate at which soils increase strength by consolidation. Drainage of soils, capillarity, and potential for frost heave are interrelated with permeability. Physical tests include:

a. Laboratory permeability tests

b. Laboratory capillarity tests

c. Field permeability tests*

d. Field infiltration rate tests

Compressibility

The amount of compression settlement of a soil due to direct loading, and the time rate at which it will occur, is influenced by soil compressibility. Of particular interest are the compression of a buried waste under the load of overlying waste and the cover soils, and the compression of sludge in a surface impoundment. (However, there are currently no well accepted procedures for determining the compressibility of these materials.) The tendency of a soil to collapse or to undergo appreciable swell-shrink is related to compressibility. Physical tests include:

a. Laboratory consolidation test

b. Swell and swell pressure tests

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* Olsen and Daniel (1981) have shown that field permeabilities may be one or more orders of magnitude greater than laboratory test derived values. Therefore, it may be appropriate to perform field permeability tests as part of the design studies or as part of the site media verification during construction.

Shear Strength

The shear strength of the natural soil influences the stability of the trench excavation and the structure foundations. The strength of compacted soil affects the behavior of embankments. Shear strength also affects the trafficability of the site roadways. Physical tests include:

a. Laboratory direct shear

b. Laboratory triaxial compression

c. Laboratory unconfined compression

Limitations of Design Properties Tests

Although the results of these tests would be ideal for quality assurance inspection during construction, they are not normally performed because they require (ASTM, 1970; Dept. of Army, 1970; Terzaghi and Peck, 1967):

a. Extensive time: The performance of any of these tests can take from one full day to as long as two weeks. Efficient control of construction requires much faster test times.

b. Complex equipment

c. Complex procedures

d. Highly skilled operators

e. Controlled laboratory environment: This often means temperature control and vibration-free surroundings not normally found at a construction site.

f. High quality undisturbed samples

Instead, various simpler, faster, index tests, whose results relate to strength, compressibility and permeability, are performed.

CONSTRUCTION INSPECTION TESTS

Any division of inspection techniques into observations and tests is necessarily arbitrary. As stated in NCHRP Synthesis 65 (TRB, 1979), "Although a test is most often thought of as a quantitative measurement of the behavior of a sample or item, in reality, a test is nothing more than an observation and can vary from complicated procedures with multiple recordings of data to a simple notation of appearance." Thus, "Skilled inspectors make tests by observation because they learn to recognize (material quality by appearance or behavior during construction operations)."

The purpose of any test or observation is to compare the material used or the work actually being performed with the desired and/or specified material and workmanship. Because of the extreme dependence of the regulatory agency on inspection documentation by the permittee for its confidence in the quality assurance program, it is essential that not only tests but observations be systematically recorded, even so-called eyeball tests. Also, since observations are a critical part of the quality assurance program, it becomes immediately obvious that their worth depends on the knowledge, experience and integrity of the observer.

Criteria for Inspection Tests and Observations

In the construction industry, the constructor's efficient utilization of his men, machinery, and materials requires that nearly continuous observations and tests be made during the progress of the work. Therefore, an observation or test made as part of the construction inspection program should:

a. Be a good indicator of a design property: That is, it should correlate well with the appropriate engineering design property either by itself or in conjunction with other, similar tests.

b. Be accurate and precise: Accuracy is a matter of systematic or consistent bias and can be improved by calibration. Precision involves random test variability which should preferably be low (See Section 3 of this report).

c. Have results quickly available: The test/observation should be capable of being performed in a time period that will allow an acceptance decision to be made before the next unit of similar work is begun. There should be minimal interference with the efficient use of the permittee's resources of construction personnel and equipment.

d. Be easily performed using simple equipment: The work should require only minimal technical expertise or training of the inspector/operator. The equipment should be rugged enough for field laboratory use, easily maintained, and easily calibrated. The test procedure must be simple and straightforward, requiring almost no judgement decisions on the part of the operator.

e. Not require an undisturbed sample, except for density

f. Provide results that are documentable: The test result should be a number that can be compared to a desired or specified value; or, it should be a simple, easily understood, consistent, and well defined descriptive term or phrase.

g. Preferably be nondestructive: The performance of a field test, or the removal of a sample for laboratory testing, often requires replacement or patching. This may then result in less than satisfactory conditions at the sample location.

These criteria are not intended to exclude any special observation or test. A balance must be maintained between the needs of the permittee for construction efficiency and the permittee's responsibility to maintain project quality.

Index Properties Tests

In the practice of geotechnical engineering, there has been developed a small group of laboratory tests called indicator, or index properties, tests. These are physical tests that generally satisfy the criteria given above for inspection tests. Some of these tests have been used for similar purposes for over 50 years.

Taylor (1948) has shown that permeability is a function of grain-size distribution, void ratio, degree of saturation, percent clay fraction, viscosity of the pore fluid, and the shape and arrangement of the pores. The shear strength of cohesive soils, according to Whitman (1960), is related to the void ratio at failure, stress history, structure (flocculated or dispersed), environmental conditions such as the temperature and the nature of the pore fluid, degree of saturation, conditions at formation of the soil, capillary tension, mineralogy, and percent clay fraction. Peck, Hanson, and Thornburn (1974) relate the shear strength of granular soils to relative density, grain-size distribution, and the shape of the grains. It generally appears that compressibility and volume stability are related to all of the relationships for shear strength and for permeability. Erodibility has empirically been associated with grain-size distribution, percent organic matter, relative permeability, and void space and pore size.

There exists in the geotechnical engineering literature a large number of empirical relationships between the engineering design properties described above and the index properties. Examples of that literature include Peck, Hanson, and Thornburn (1974), Sowers (1979), Lo (1980), the Navy Design Manual, NAVFAC DM-7.1 (Dept. of the Navy, 1982), and the Earth Manual (USBR, 1974).

Peck, Hanson, and Thornburn (1974) state "If the...tests are properly chosen, soils or rock materials having similar index properties are likely to exhibit similar engineering behavior." Also, "In addition to their value in the correlation of construction experience, they provide a means for checking the correctness of the field identification of a given material. If the material has been improperly identified, the index properties indicate the error and lead to correct classification."

The index properties tests useful in an inspection program may be placed into three categories:

a. Weight-volume relationships

    (1) Water content test

    (2) Density test

    (3) Specific gravity test*

---

* Usually the specific gravity values established for each soil type during site characterization are used for calculations during the routine QA tests. The variability of specific gravity within a woil layer or geologic unit is usually very small. Harr (1977) reports a coefficient of variation of only 1-4 percent (See Table 3).

(4) Calculated values: void ratio, porosity, and degree of saturation

b. Soil classification tests*

(1) Grain-size distribution tests

(2) Atterberg limits tests

(3) Consistency tests: using simple field methods

(4) Calculated values: plasticity index, liquidity index, activity, and USCS Classification

c. Laboratory compaction tests

(1) Density/water content/compactive effort tests; for cohesive soils and "dirty" (i.e. by the USCS those soils classified as GM, GC, SM, or SC) granular soils

(2) Maximum and minimum density tests; for clean (i.e. by the USCS those soils classified as GW, GP, SW or SP) granular soils

All of the index properties result from standardized soils tests (Dept. of Army, 1970; USBR Earth Manual, 1974; and ASTM, Pt. 19, 1982). They are defined as follows:

Natural water content: The natural water content of a soil is defined as the weight of water in the soil expressed as a percentage of dry weight of solid matter present in the soil. The water content is based on the loss of water at an arbitrary drying temperature of 105° to 110°C.

Density: The mass density of a soil material is its weight per unit volume. The dry density of a soil is defined as the weight of solids contained in the unit volume of the soil and is usually expressed in pounds per cubic foot. Various weight-volume relationships are presented in Figure 2.

Specific gravity: The specific gravity of the solid constitutents of a soil is the ratio of the unit weight of the solid constituents to the unit weight of water.

Void ratio: The void ratio of a soil is calculated as the ratio of volume of voids to the volume of the soil solids.

Porosity: The porosity of a soil is calculated as the ratio of the volume of voids to the total volume of soil, which includes air, water, and solids.

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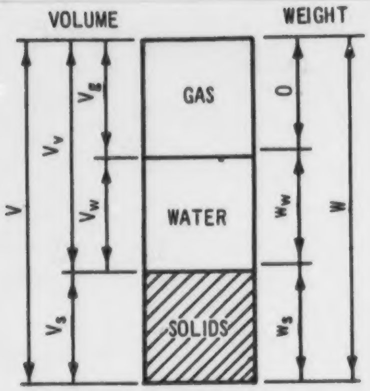
* Soil classification by the Unified Soil Classification System (USCS) uses only grain-size distribution tests for coarse grained soils or Atterberg limits tests for fine grained soils. Borderline or questionable classifications require both tests.



WATER CONTENT $w = \frac{W_w}{W_s}$

SPECIFIC GRAVITY $G_s = \frac{W_s}{V_s \gamma_w}$

VOLUME OF SOLIDS $V_s = \frac{W_s}{G_s \gamma_w}$

VOLUME OF VOIDS $V_v = V - V_s$

VOID RATIO $e = \frac{V_v}{V_s} = \frac{n}{1 - n}$

POROSITY $n = \frac{V_v}{V} = \frac{e}{1 + e}$

DEGREE OF SATURATION $S = \frac{V_w}{V_v} = \frac{w G_s}{e}$

UNIT WEIGHT OF WATER (FRESH WATER) $\gamma_w = \frac{W_w}{V_w} = 62.4$ PCF

DRY UNIT WEIGHT $\gamma_d = \frac{W_s}{V} = \frac{\gamma_m}{1 + w}$

WET UNIT WEIGHT $\gamma_m = \frac{W}{V}$

SUBMERGED (BOUYANT) UNIT WEIGHT $\gamma' = \gamma_m - \gamma_w = \frac{G_s - 1}{1 + e} \gamma_w$

Figure 2. Weight-volume relationships

Degree of saturation: The degree of saturation is calculated as the volume of water as a percentage of the total volume of voids. Thus, at 100% saturation, all of the void space is occupied by water, and at 0% saturation, all of the void space is occupied by air.

Grain-size distribution: The grain-size distribution of soils is determined by means of sieves and/or a hydrometer analysis, and the results are expressed in the form of a cumulative semilog plot of percentage finer versus grain diameter. Typical grain-size distribution curves are shown in Figure 3. The knowledge of particle-size distribution is of particular importance when coarse grained soils are involved. Useful values are: (a) the effective size, which is defined as the grain diameter corresponding to the 10% finer ordinate on the grain-size curve; (b) the coefficient of uniformity which is defined as the ratio of the D_{60} size to the D_{10} size (Figure 3); (c) the coefficient of curvature, which is defined as the ratio of the square of the D_{30} size to the product of the D_{10} and D_{60} sizes (Table 1); and (d) the 15 and 85 percent sizes, which are used in filter design.

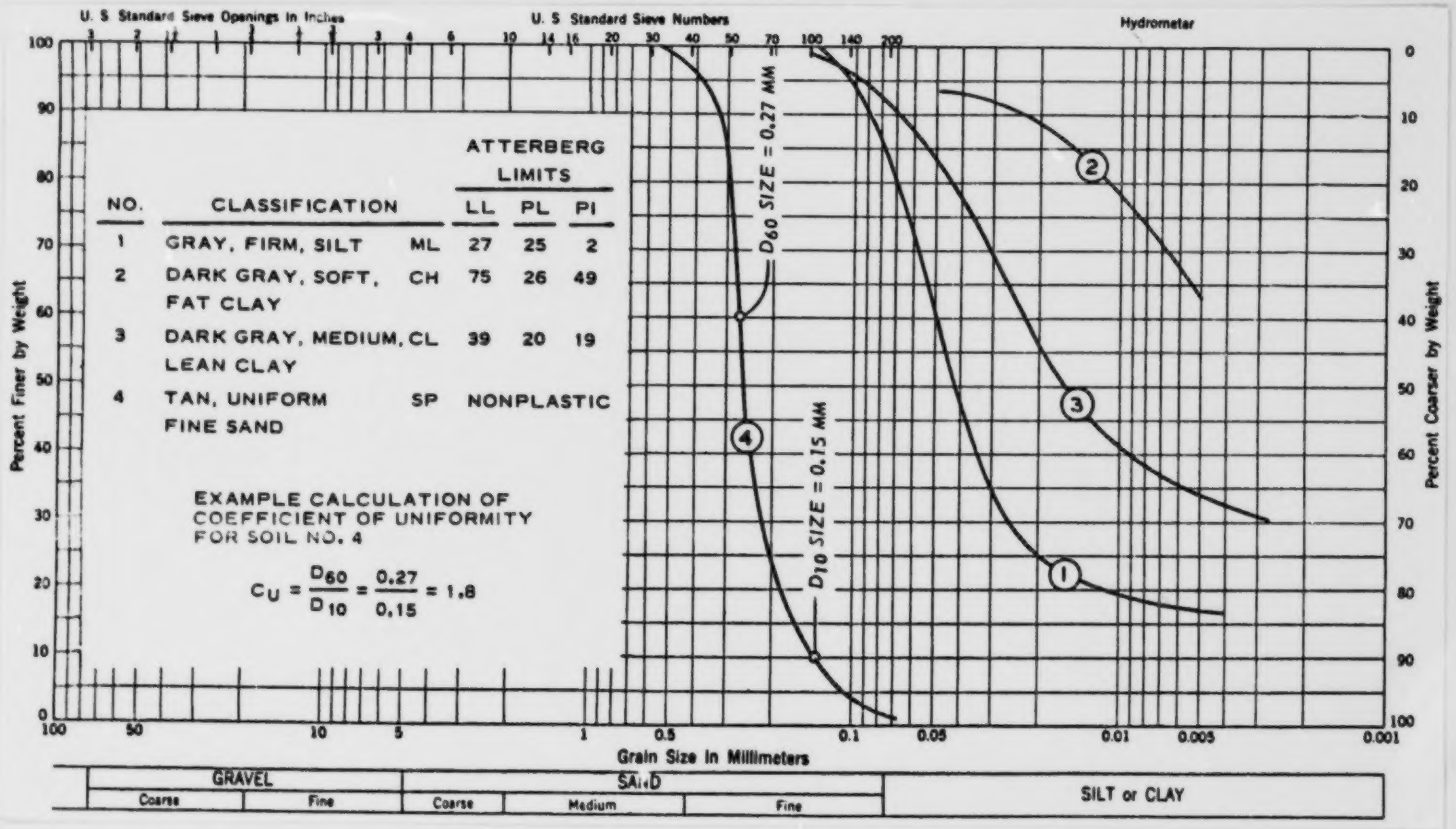
Atterberg Limits: The Atterberg limits indicate the range of water content over which a cohesive soil behaves plastically. The upper limit of the range is known as the liquid limit (LL), the lower as the plastic limit (PL). The LL is the water content at which a soil will just begin to flow when slightly jarred in a prescribed manner. The PL is the water content at which the soil will just begin to crumble when rolled into threads 1/8 inch in diameter. The general relationship of the limits to water content is shown in Figure 4. Highly plastic clays that have a high content of colloidal particles have a high LL, while lean clays having a low content of colloidal particles have a correspondingly low LL. A decrease in LL and PL after either oven or air drying usually indicates the presence of organic matter. The Atterberg limits are, with the percent clay sizes, a good indicator of clay fraction mineralogy. The ratio of the plasticity index to the percent (finer than 0.002 mm) clay is called the "activity" of a clay, which correlates well with mineralogy.

Plasticity index: The plasticity index (PI) is calculated as the difference between the liquid limit (LL) and the plastic limit (PL) water contents, i.e., PI = LL - PL.

Liquidity index: The liquidity index (LI) is calculated as the natural water content (w_n) minus the PL divided by the PI, i.e., LI = (w_n - PL)/PI. The LI is a measure of the consistency of soils. Soft clays have an LI approaching 100 percent; whereas, stiff clays have an LI approaching zero.

Soil classification: The Unified Soil Classification System, based on the identification of soils according to their grain-size distributions, plasticity characteristics, and on their grouping with respect to behavior, is widely used to classify soils in connection with geotechnical design. Table 1 summarizes the Unified Soil Classification System and also presents field identification procedures for fine grained soils or soil fractions.

Consistency: The consistency of an undisturbed cohesive soil may be expressed quantitatively by the unconfined compressive strength, q_u. Qualitative



NO.	CLASSIFICATION		ATTERBERG LIMITS LL	PL	PI
1	GRAY, FIRM, SILT	ML	27	25	2
2	DARK GRAY, SOFT, FAT CLAY	CH	75	26	49
3	DARK GRAY, MEDIUM, LEAN CLAY	CL	39	20	19
4	TAN, UNIFORM FINE SAND	SP	NONPLASTIC		

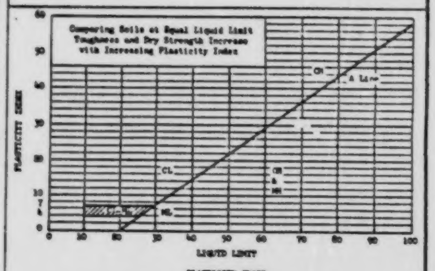
EXAMPLE CALCULATION OF COEFFICIENT OF UNIFORMITY FOR SOIL NO. 4

$$C_U = \frac{D_{60}}{D_{10}} = \frac{0.27}{0.15} = 1.8$$

Figure 3. Typical grain-size distribution curves for soils

TABLE 1. UNIFIED SOIL CLASSIFICATION SYSTEM

Major Divisions			Group Symbols	Typical Names	Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)	Information Required for Describing Soils	Laboratory Classification Criteria	
1	2		3	4	5	6	7	
Coarse-grained Soils More than half of material is larger than No. 200 sieve size. The No. 200 sieve size is about the smallest particle visible to the naked eye.	Gravels More than half of coarse fraction is larger than No. 4 sieve size. (For visual classification, the 1/4-in. size may be used as equivalent to the No. 4 sieve size)	Clean Gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines.	Wide range in grain sizes and substantial amounts of all intermediate particle sizes.	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions, and drainage characteristics.	Use grain-size curve in identifying the fractions as given under field identification. Determine percentages of gravel and sand from grain-size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse-grained soils are classified as follows: Less than 5% - GW, GP, SW, SP. More than 12% - GM, GC, SM, SC. 5% to 12% - Borderline cases requiring use of dual symbols.	$C_u = \frac{D_{60}}{D_{10}}$ Greater than 4 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			GP	Poorly graded gravels or gravel-sand mixtures, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Not meeting all gradation requirements for GW
		Gravels with Fines (Appreciable amount of fines)	GM	Silty gravels, gravel-sand-silt mixture.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).	Give typical name; indicate approximate percentages of sand and gravel, maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbol in parentheses.		Atterberg limits below "A" line or PI less than 4 Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			Atterberg limits above "A" line with PI greater than 7
	Sands More than half of coarse fraction is smaller than No. 4 sieve size.	Clean Sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines.	Wide range in grain size and substantial amounts of all intermediate particle sizes.			$C_u = \frac{D_{60}}{D_{10}}$ Greater than 6 $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			SP	Poorly graded sands or gravelly sands, little or no fines.	Predominantly one size or a range of sizes with some intermediate sizes missing.			Not meeting all gradation requirements for SW
		Sands with Fines (Appreciable amount of fines)	SM	Silty sands, sand-silt mixtures.	Nonplastic fines or fines with low plasticity (for identification procedures see ML below).	Example: Silty sand, gravelly; about 20% hard, angular gravel particles 1/2-in. maximum size; rounded and subangular sand grains, coarse to fine; about 15% nonplastic fines with low dry strength; well compacted and moist in place; alluvial sand; (SM).		Atterberg limits below "A" line or PI less than 4 Above "A" line with PI between 4 and 7 are borderline cases requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures.	Plastic fines (for identification procedures see CL below).			Atterberg limits above "A" line with PI greater than 7

Major Divisions		Group Symbols	Typical Names	Identification Procedures on Fraction Smaller than No. 40 Sieve Size			Information Required for Describing Soils	Laboratory Classification Criteria
				Dry Strength (Crushing characteristics)	Dilatancy (Reaction to shaking)	Toughness (Consistency near PL)		
Fine-grained Soils More than half of material is smaller than No. 200 sieve size.	Silts and Clays Liquid limit is less than 50	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.	None to slight	Quick to slow	None	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remolded states, moisture and drainage conditions.	 PLASTICITY CHART For laboratory classification of fine-grained soils
		CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays.	Medium to high	None to very slow	Medium		
		OL	Organic silts and organic silty clays of low plasticity.	Slight to medium	Slow	Slight	Give typical name; indicate degree and character of plasticity; amount and maximum size of coarse grains; color in wet condition; odor, if any; local or geologic name and other pertinent descriptive information; and symbol in parentheses.	
	Silts and Clays Liquid limit is greater than 50	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.	Slight to medium	Slow to none	Slight to medium		
		CH	Inorganic clays of high plasticity, fat clays.	High to very high	None	High		
		OH	Organic clays of medium to high plasticity, organic silts.	Medium to high	None to very slow	Slight to medium	Example: Clayey silt, brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (ML).	
Highly Organic Soils		Pt	Peat and other highly organic soils.	Readily identified by color, odor, spongy feel and frequently by fibrous texture.				

Comparing Soils at Equal Liquid Limit
Toughness and Dry Strength Increase
with Increasing Plasticity Index
PLASTICITY INDEX
LIQUID LIMIT
CH
A Line
CL
OH & MH
CL-ML
ML
0
4
7
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
100

(1) Boundary classifications: Soils possessing characteristics of two groups are designated by combinations of group symbols. For example GW-GC, well-graded gravel-sand mixture with clay binder. (2) All sieve sizes on this chart are U. S. standard.

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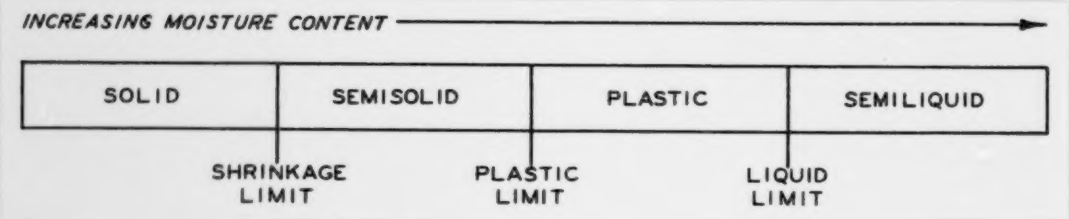


Figure 4. Relationship of Atterberg limits to water content

expressions for the consistency of clays in terms of q_u are given in Table 2. If equipment for making unconfined compression tests is not available, a rough estimate can be made based on the simple field identification suggested in the table; various small handheld penetration or vane devices are also helpful.

Compaction tests: Compaction tests are performed on cohesive soils and on dirty coarse grained soils. At a constant compactive effort, an impact or kneading compaction is applied at various water contents. The result is a density/water content relationship, such as shown in Figure 5, in which the maximum density and the optimum water content are defined. Test results vary with changes in soil type, type of compaction, and compactive effort.

Relative density tests: For clean, coarse grained soils the maximum achievable density (by vibration) and minimum achievable density (by pouring) are compared to an in situ soil density. The in situ value is then calculated relative to the laboratory defined maximum and minimum values for the same soil. It is possible to have field densities greater than the maximum or less than the minimum since these values are defined by the results of certain standardized tests. An example is given in Figure 6.

Compaction tests and/or relative density tests are generally used to establish limits or goals for field compactive effort. The attainment of a specified degree of compaction is expected to provide a compacted fill soil having the desired engineering design properties, i.e. permeability, compressibility, and shear strength.

Additional Tests

There is, in addition to the laboratory index properties tests described above, a small group of useful tests which, because of their simplicity, almost classify as observations. They include the field expedient tests of Table 1.

Field expedient tests: These soil identification tests are based on visual examination and simple manual tests; they do not yield a numerical result. They are described in detail in ASTM (1982) Designation D 2488-69, "Standard Recommended Practice for Description of Soils (Visual-Manual Procedure)".

Color: The color of a soil sample, particularly in its natural moisture condition, is a useful method for correlating similar soils and for identifying water table conditions. A formal method using Munsell color charts is available for classification by colors (Spangler and Handy, 1982).

Organic content: ASTM (1982) Designation D 2488-69 and various geotechnical textbooks describe expedient methods for identifying organic soils. These methods include observation of the soil's dark color or earthy odor. Heating or hydrogen peroxide solution will destroy the organic matter, permitting classification. Formal chemical analysis methods are referenced in Section 4.

TABLE 2. DETERMINATION OF THE CONSISTENCY OF CLAYS

Unconfined Compressive Strength, q_u tsf	Field Identification	Consistency
Less than 0.25	Easily penetrated several inches by fist	Very soft
0.25 - 0.5	Easily penetrated several inches by thumb	Soft
0.5 - 1.0	Can be penetrated several inches by thumb with moderate effort	Medium
1.0 - 2.0	Readily indented by thumb but penetrated only with great effort	Stiff
2.0 - 4.0	Readily indented by thumbnail	Very stiff
Over 4.0	Indented with difficulty by thumbnail	Hard

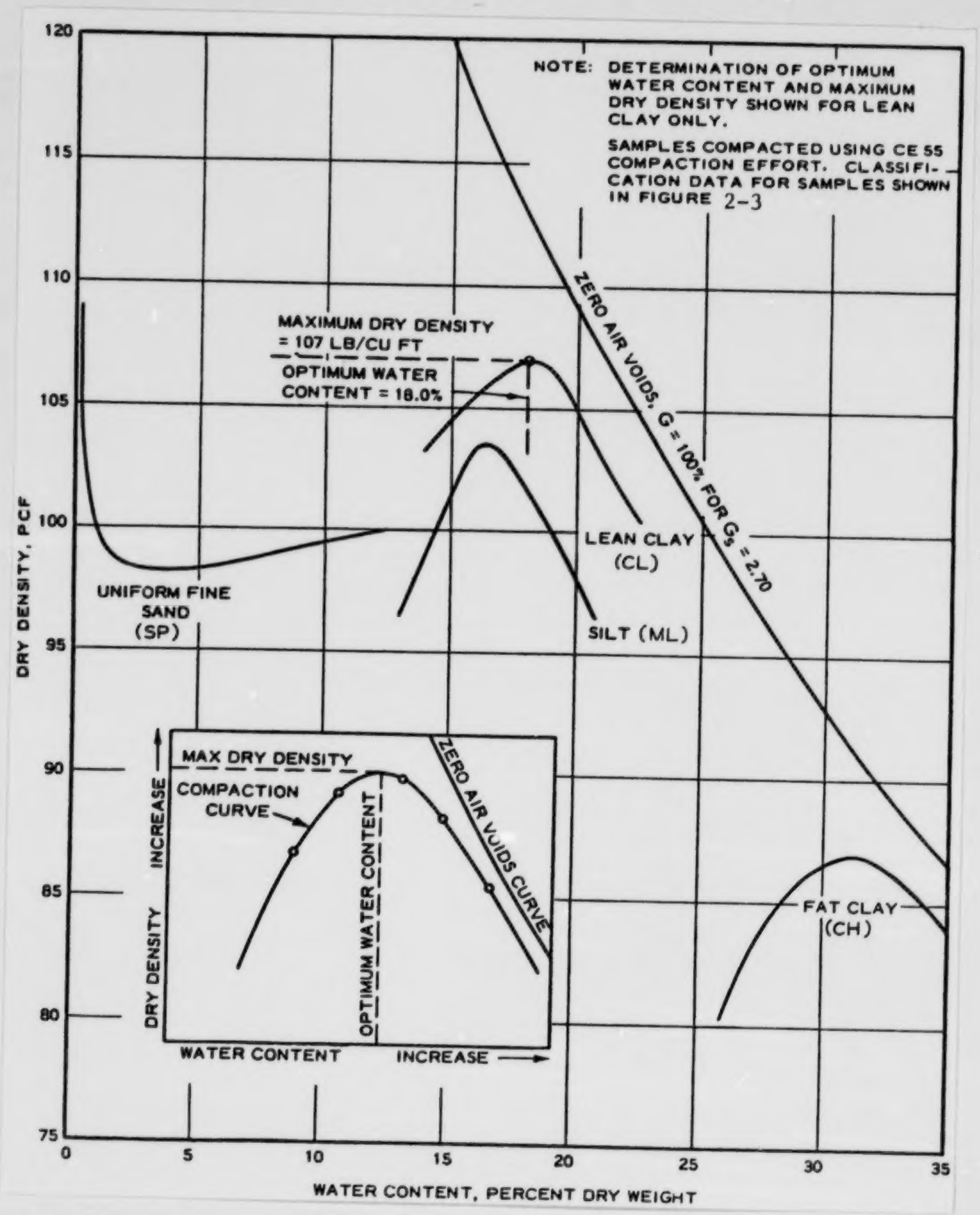
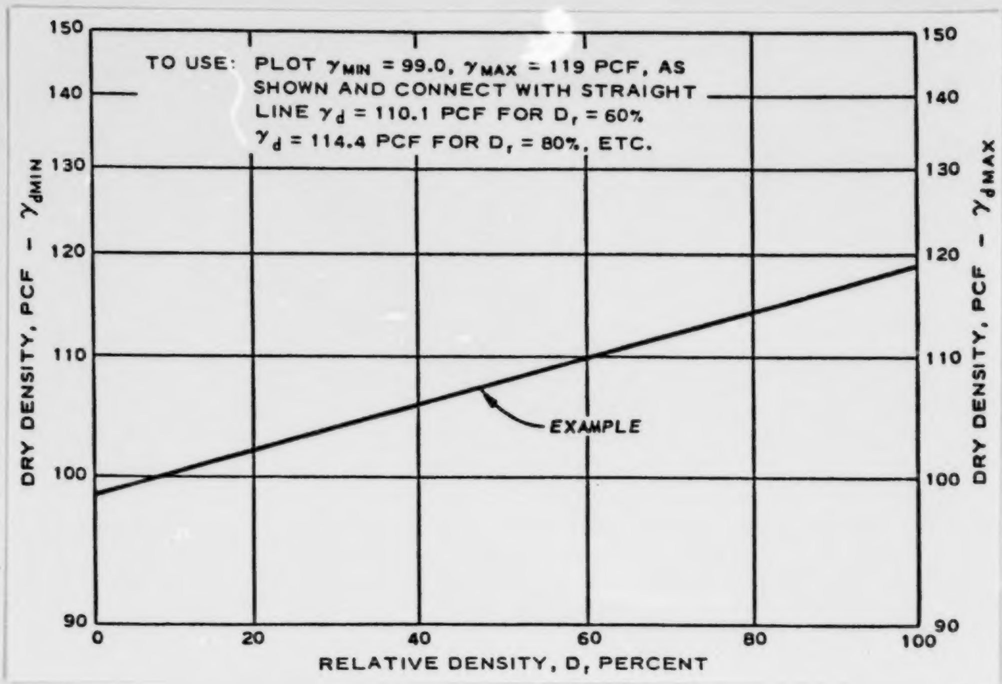


Figure 5. Typical density-water content relationships for compacted soils



TO USE: PLOT $\gamma_{MIN} = 99.0$, $\gamma_{MAX} = 119$ PCF, AS SHOWN AND CONNECT WITH STRAIGHT LINE $\gamma_d = 110.1$ PCF FOR $D_r = 60\%$ $\gamma_d = 114.4$ PCF FOR $D_r = 80\%$, ETC.

$$D_r \text{ , percent} = \left(\frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}}\right) \times \left(\frac{\gamma_{dmax}}{\gamma_d}\right) \times 100$$

where

D_r = relative density, in percent

γ_d = dry unit weight of the soil in place, called "in-place" density

γ_{dmin} = dry unit weight of the soil in the loosest state which can be attained in a particular laboratory test called "minimum density"

γ_{dmax} = dry unit weight of the soil in the densest state which can be attained in a particular laboratory test called "maximum density"

Figure 6. Example of graphical solution of relative density relationship

THE POST-PERMIT STAGE

This section of the report presents those geotechnical observations and/or tests that should be made and documented during the construction, operation, and closure of a disposal site. The presentation is made in the context of the various unit processes involved. The observations/tests and documentation will be the same for the same unit process, regardless of its location on the project.

Only those unit processes, or portions of processes, whose quality of materials and workmanship directly affect the ability of the site to meet specified performance standards are presented. The emphasis in the discussion presented for each process is on a quality assurance program that focuses on catching mistakes before or as they occur, correcting them, testing for specification compliance, and documenting the entire process to provide the necessary confidence in the inspection procedure. During the conduct of each unit process, there must be continuous, cooperative interaction between the groups within the permittee's forces responsible for the design function, the inspection function, and the construction and operations function to secure the required verification of design assumptions and quality of work, along with the effective, efficient, and profitable use of men, machinery, and materials.

Inspection Reports

Documentation of the necessary site geotechnical verification work, the required inspection observations and tests, and their interpretation, should be part of the total project record. As will be presented in greater detail in Section 5 of this report, the project records will include daily inspection reports, field/laboratory data sheets, block* evaluation reports, design acceptance reports, and a summary.

Site Preparation

The process of site preparation includes clearing, grubbing, stripping, and grading (U.S. Bureau of Reclamation, 1974; Church, 1981; and Dept. of the Army, 1977). The primary purposes for this activity are (a) preparation of each specific disposal facility for excavation and/or embankment placement, (b) construction of haul roads, and (c) altering the site drainage patterns. The following observations/tests should be made and documented:

a. Observations of the exposed ground surface in the site limits, following stripping, as part of site media confirmation. Normally, only the visual-manual field identification procedures shown in Table 1, Unified Soil Classification System or ASTM (1982)

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* The term block is used in this report in preference to the more commonly used term, lot, from the field of Statistical Quality Control. It is the authors' opinion that the word lot implies a number of discrete units from a continuous manufacturing process. The term block is more appropriate to bulk materials such as a soil mass.

Designation D 2488-69, will be necessary. If an unexpected material or zone configuration is encountered, then more formal tests may be necessary.

b. Observation of ground surface contouring measurements to confirm adherence to the planned drainage pattern, preferably these should be surveyed measurements

c. Observation of the performance of the surface drainage system, during the first significant rainfall, to identify erosion or ponding problems

Excavation

The preparation of a disposal facility may involve (a) the excavation of one or more trenches below the ground surface, and/or (b) the stripping and shaping of a natural or man-made depression. The latter may be a gully, small canyon, or similar erosional feature, wholly or partially enclosed by an earthfill embankment, or it may be a former strip mine, borrow pit, or similar feature. All are characterized by having the floor and at least one wall consisting of the stripped and shaped, naturally occurring site soils.

The observations and tests that should be made and documented regarding the excavated walls and floors of a disposal facility include:

a. Detailed observations and descriptions should be made of the exposed walls and floor for the purpose of site media confirmation. These should be supplemented by confirmation tests for those features that conform to the site characterization studies. Photographs are often of value. The tests will usually consist of field consistency tests and those tests required for the USCS classification, i.e., grain-size distribution and/or Atterberg limits. More extensive testing may be necessary if an unanticipated material or zone configuration is encountered. Undisturbed samples and engineering properties tests may be justified, with additional samples tested for index properties. Observed differences from expected site characterization should not only be recorded, but should also be immediately reported to the permittee's group responsible for the design function for their consideration of possible remedial action.

b. Observations should be recorded of the construction surveys involving trench location, slopes of walls, and slopes of floors. Conformance with planned slopes should be noted.

c. During and after construction, visual observations, supplemented by surveying where necessary, should be made and recorded of excavation related soil movements. These should include heaving and/or cracking of the floor, and of slaking, sluffing, creep, sliding, or other movements of the side walls. Again, photographs may be of great documentary value. Survey monuments, placed at the start of construction, should provide documentable data.

d. Observations should be recorded of erosion controls for conformance with plans. These may include trench-top perimeter ditches and/or dikes and the placement of any spray-on erosion-inhibiting material, including the material's identification and application rate.

Foundation Preparation

If an earthfill embankment is used to partially or completely enclose a disposal facility, the natural foundation and abutments must, as discussed in Engineer Manual 1110-2-1911 (Dept. of Army, 1977), (a) provide positive control of underseepage, (b) provide satisfactory contact with overlying compacted fill, and (c) minimize differential settlements and thereby prevent cracking in the fill. The observations and tests made and recorded during foundation preparation should include:

a. Observations should be recorded of the stripping to assure that all soft, organic, or otherwise undesirable materials are removed. Consistency (Table 2) may be checked by a hand penetrometer or similar device. Proof-rolling by construction equipment is often used to locate soft areas. Organic soils may be identified by the procedures given in Table 1.

b. Observations should be recorded of the soil and rock surfaces for smoothness, adequate cleaning, filling of rock joints and of depressions.

c. Observations should be recorded of the construction of underseepage cutoffs, if used, to check required depth, materials encountered, backfill materials used, and proper placement of backfill. If compacted fill is used, then it should be observed/tested as for other fills as discussed below.

Compacted Earthfill

Compacted earthfill embankments may be used to partially or completely enclose a disposal facility. Where a liner is used, it may include a compacted soil hydraulic barrier and a compacted granular hydraulic conductor layer. The final cover may also include a hydraulic barrier and a hydraulic conductor layer, overlain by a vegetation supporting layer.

The waste contained by the embankment and/or liner system may, in a disposal facility, consist of solid wastes with moist soil backfill which may eventually become saturated with water, or in the case of a surface impoundment, it may consist of a high water content slurry. If appreciable steady-state seepage is expected through the embankment, then internal seepage control features such as filter drains and underseepage control measures may be needed. The liner system may contain a hydraulic barrier, such as a geomembrane, supported by a compacted, low permeability cohesive soil. It may also contain a hydraulic conductor, usually a granular filter material of high permeability, connected to a leachate collector system.

The observations and tests that should be made (Dept. of the Army, 1977;

and USBR, 1973) and recorded during compacted fill placement, using cohesive or granular soils, are presented below (A similar discussion of off-site materials placed on, or incorporated into, the compacted soil part of the liner system is given later in this report.):

a. The quality of the borrow materials must be tested. The source of the borrow may be a natural borrow pit or a stockpile of soil from a trench excavation. Two or more soils may be blended to produce a desired gradation or plasticity. Samples of the borrow materials should be tested for USCS classification (grain-size distribution and/or Atterberg limits) and for natural water content. If admixes are blended into the natural soil, the application rate and uniformity of mixing should be observed and documented.

b. Atmospheric conditions should be recorded. Compaction specifications often place restrictions on work performed just after a rainfall during very hot or windy weather, or during freezing conditions.

c. Equipment type, size and compatibility with the soil type must be evaluated and recorded. For cohesive soil, a sheepsfoot roller, a tamping roller, or a rubber tired roller may be used. For clean, granular soil, a vibratory roller is appropriate. As given in Engineer Manual 1110-2-1911 (Dept. of the Army, 1977), items to be checked and recorded include: (a) for a sheepsfoot roller, drum diameter and length, empty weight and ballasted weight, arrangement of feet and length and face area of feet, and the yoking arrangement; (b) for a rubber tired roller, the tire inflation pressure, spacing of tires, and the empty and ballasted wheel loads; and (c) for a vibratory roller, the static weight, imparted dynamic force, operating frequency of vibration, and the drum diameter and length.

d. The uncompacted or loose lift thickness should be systematically measured at several statistically valid locations in a layer of fill. Both actual thickness and uniformity of lift placement are of importance. Loose lift thicknesses of (a) 6 to 8 in. for a sheepsfoot roller, or (b) 9 to 12 in. for a 50 ton rubber tired roller are usual for cohesive soils; while clean, granular soils should have loose lifts of (c) 6 to 15 in. when using a vibratory roller or 50 ton rubber tired roller, or (d) 6 to 8 in. when using a crawler tractor (Dept. of the Army, 1977). Measurements are usually made with a marked staff or shovel blade, although survey levels should be made every few lifts for verification and documentation.

e. Compactive effort and uniformity of compaction should be observed and recorded. Compactive effort can be changed by changing the number of passes of the roller, by changing the size and weight of the roller, and/or by changing lift thickness. For cohesive soils (a) six to eight passes of a sheepsfoot roller or (b) four coverages of a 50 ton rubber tired roller are usual; while for a clean, granular soil (c) three or four passes of a vibratory roller or (d) three to six coverages of a crawler tractor are usual (Dept. of the Army, 1977).

Uniformity of coverage should be closely observed, particularly at fill edges and in turn around areas. When a crawler tractor is used, the coverages must be by the tracks of the tractor.

f. Compacted density and water content should be measured and recorded. The coordinate location of each test and the elevation of the ground surface should also be measured. The latter is a check on lift thickness; and when a retest of unacceptable fill is necessary, serves to verify that no additional fill has been placed.

g. Laboratory compaction tests should be made of samples of the same fill soil whose field density and water content were measured in item (f.) above. The effectiveness of the compactive effort in the field is referenced to the laboratory compaction test. Specifications for cohesive soil and dirty granular soil compaction require achievement of a minimum percentage of the maximum density, at a water content within a specified range and related to the optimum water content, as determined by the specified laboratory compaction test procedure. Figure 5 shows typical impact-compaction laboratory test results. For clean granular soils, which densify more readily under vibration than under impact, a minimum relative density or a minimum percentage of the laboratory maximum dry density is usually specified. This involves comparison of the density of the field compacted soil with the maximum and minimum densities for the same soil developed in a specified laboratory procedure. Figure 6 shows a graphical comparison procedure using an ordinate for dry density scaled for solution of the relative density equation.

Liner Materials and Geotextiles

The construction of a hazardous waste disposal facility may include the construction processes involved in liner material or geotextile installation. The hydraulic barrier layer of the liner is expected to provide a permeability lower than a required value. When this criterion is not present in the natural cut soil of the floor and walls or cannot be effectively achieved in a compacted soil fill layer, then off-site materials may be used. These may consist of bentonitic clay, portland cement, asphalt, lime, or similar materials that are admixed throughout, or are mixed with only the surface lift of the compacted soil of the barrier. The barrier may also be a spray-on material or a geomembrane. Geotextiles may also be used as a filter aid or for soil reinforcement, e.g. slope stability or trench cap strength.

The tests and observations that should be made and recorded during liner material or geotextile installation are generally material dependent:

a. For all off-site materials used (liner materials and geotextiles) the type and supplier's identification for the material should be recorded. Lot numbers or their equivalent are used to trace materials of substandard quality to specific manufacturing procedures.

b. For bentonitic clay and admixed material liners the tests and observations are those that would be conducted to determine the field permeability of any soil layer, i.e. to include density testing and observation of layer thickness. (These tests and observations are discussed in the previous subsection on Compacted Earthfill.)

c. The tests and observations for the installation of a portland cement or asphalt liner are deemed to be beyond the scope of this report as they are not within the framework of soils engineering per se. References describing these tests and observations are readily available from the Portland Cement Association and the Asphalt Institute.

d. For admixed materials, the spreading and mixing, or blending equipment and procedures should be observed and recorded. Reference should be made to industry standard methods, to manufacturer's recommended procedures, or other descriptions of the state of the art for the methods.

e. For admixed materials, the application rate should be observed and recorded. The methods used for verifying the application rate, such as the calibration of spreading devices, should also be recorded.

f. For admixed materials, compaction of the soil-admixture blend should be observed, tested, and recorded in the same manner as described earlier for Compacted Earthfill. Soil classification tests, observations of lift thickness and of uniformity of rolling, observations of the suitability of blending and compacting equipment, and the comparison of field density (and water content, if applicable) with the specified laboratory control test, should all be made and recorded.

g. For spray-on materials, the observations and tests include identification of the material, verification of manufacturer's quality tests, application equipment suitability, application technique comparison with state-of-the-art directions, application rate, application thickness, and uniformity of coverage.

h. For geomembranes or geotextiles, the supplier's materials identification marks should be compared with the purchase order or catalog descriptions. The smoothness of the placement surface, and its freedom from objects that might puncture the material, should be verified. If required, test specimens may be cut from the field sheets; this will require patching and the patching itself should also be observed and recorded. The method of placement of the material should be recorded and supplemented by photographs if possible. The seams should be inspected at frequent locations and the required seam overlap measured and recorded. The method of sealing the seam, whether thermal or adhesive, should be observed and recorded; all seam formation should be closely inspected. Seam integrity tests, if specified, should be made and the results recorded, including notation of the locations of the tests. The entire placed material should be systematically inspected for imperfections or tears and the results of the inspection recorded. When appropriate, as determined by the permittee's forces (e.g. for a surface impoundment), a hydrostatic leak detection test may be performed. If a hydrostatic leak detection test is performed then the entire submerged geomembrane should be systematically inspected for leaks.

Hydraulic Collector System

The disposal facility bottom liner and the final cover may both contain a permeable layer above the hydraulic barrier. Its function is to change the direction of the percolating water from a downward movement to a horizontal movement toward a nearby collector drain. Usually it is formed of a clean granular material placed directly on the surface of the impermeable hydraulic barrier. The surface of the barrier is sloped toward the collector system, usually located at the perimeter of the disposal unit. Observations and tests that should be made and recorded for this feature are:

a. The surface of the base for the permeable layer should be inspected and observations recorded. Imperfections include soft soils, organic materials, the lack of specified admix or spray-on material, or leaks in a geomembrane.

b. The amount and direction of slope of the permeable layer base should be verified and recorded. This will usually involve standard surveying techniques.

c. The clean granular materials used in the permeable layer should be tested for grain-size distribution, particularly for the presence of undesirable fines. Comparison should be made to the specified grain-size requirements.

d. The placement, compaction, field density testing, and relative density testing should be performed and recorded as described above for Compacted Earthfill.

SECTION 3

SAMPLING METHODS AND SELECTION OF SAMPLE SIZE

There is an inherent, or natural, random variability in measurement data for any specified quality characteristic of any soil mass, or other construction material, whether natural or construction processed (Terzaghi and Peck, 1967). This is due to natural, point-to-point, variations in material quality and random variations due to the sampling and testing procedures. It is assumed in this discussion that this natural variability has been considered, either formally or intuitively, in the establishment of (a) the design assumptions regarding the engineering properties of the existing site media and (b) the specifications for materials and workmanship in the construction processes.

Inspection of the existing site media exposed during construction, and of the material and workmanship of the construction processes, is an essential part of the construction quality assurance program. Where a 100 percent inspection is not practical or is clearly uneconomical, one or more samples are obtained and tested. The resulting sample data are used to estimate a quality characteristic of the soil mass they represent. The usefulness of samples in representing the soil mass is a function of the manner of sampling, i.e. the size of the soil mass (block), the manner of selecting sampling locations and times, the number of samples or measurements per block, and the sampling and testing procedure. These, in turn, affect the method of evaluation of the sample with regard to specified or assumed quality characteristics.

The establishment of sampling methods and of sampling and testing frequency may be based on either (a) judgement or experience, or (b) probabilistic methods using statistical theory (Deming, 1950). Up until the last 10 to 15 years, Willenbrock (1976) states, "...quality of construction was largely accomplished through semi-artisan techniques and procedures with constant visual inspection." Judgement methods were, and still are, subject to biases and sampling errors (Deming, 1950) dependent on the knowledge, capability, and experience of the specification writers, the inspector, and/or his supervisor. These factors cannot easily be evaluated or documented. Therefore the more rational, calculable, and documentable methods using statistical theory are recommended. The human factor (see Section 5), with its prejudice and bias, can thus largely be eliminated. If sampling, whether judgemental or random, is to be used to evaluate and/or control compaction or any other construction process, then it is imperative that a well defined procedure be used consistently. If the procedure is altered, then a change in population characteristics occurs, and the sample becomes biased.

As background for the presentation of sampling and testing frequency, the natural variability of measured engineering soil properties is discussed. Several sources of variability data from the engineering literature are presented as preliminary sources for obtaining data. The sources of variability in soils, as measured by the various index properties tests, is presented. This is followed by a discussion of accuracy and precision of measurements. The effect of test method precision is developed as it relates to selection among alternative test methods. Types of inspection and sampling plans are presented. Forms of random sampling plans are recommended and illustrated by an example. The rational selection and/or evaluation of sample size, based on quality variance, maximum expected error, and confidence level, is presented in statistical terms. Finally, the statistical methodology and interpretation of calibration and sample size are given.

Although this section of the report discusses sampling and testing using statistical analysis terms, equations, and tables, it is not intended to be a complete treatise on the subject. Its aim is to introduce the topic and describe its application to quality assurance in hazardous waste disposal facility construction. The interested reader should consult more complete discussions of the various topics in standard textbooks on engineering statistics and professional journal articles.

VARIABILITY OF MEASURED PROPERTIES

Soils are generally used in their natural state, unaltered by the homogenizing manufacturing processes of, for example, structural metals, portland cement, or asphalt cement. The measured properties of interest in this discussion are those given in Section 2: the engineering soil properties; the soil index properties; the specified quality characteristics of off-site materials; and many of the observations of construction processes. This discussion can easily be extended to include geochemical and geohydrologic properties.

The variability in the properties of natural soils, whether undisturbed or processed, has been recognized for some time by geologists, soil scientists, and geotechnical engineers (Terzaghi and Peck, 1967). The literature of these disciplines, particularly since the middle 1950's, contains many studies of soil property variability. The literature is so voluminous that it would be burdensome for this report to reference all of it. Therefore, only a few, representative reference sources will be given.

Natural Soil Deposits

The variability of the properties of natural soil deposits is discussed in general terms in most textbooks on geotechnical engineering and engineering geology. Very good descriptions are given, for example, in Peck, et al. (1974), Harr (1977), Sowers (1979), and Spangler and Handy (1982). Studies of the variation of soil index properties in soil survey mapping units were given in Thornburn, et al. (1970) and Campbell (1978). An interesting study of field infiltration rate variation over a limited site was given by

Vieira, et al. (1981); this information may be of value in planning testing programs for verifying the permeability of existing site media, compacted clay liners and covers. Harr (1977) has compiled data from a number of literature sources. Table 3 is a summary of Harr's tabulations.

Compacted Soils

The published data for compacted soils comes mainly from two sources: (1) earth dams and (2) highway embankments construction. Davis (1953) first reported statistical evaluation of control tests for Bureau of Reclamation dams. Several Corps of Engineers projects were evaluated for water content and density variation by Turnbull, Compton, and Ahlvin (1966). They showed moisture content had a standard deviation from 1.2 to 1.9 percent and that density had a standard deviation from 1.88 to 2.32 lb/cu ft. Davis (1966) summarized earthwork control statistics from 72 Bureau of Reclamation earth dams. He concluded that fill moisture content had a standard deviation of less than about 1.5 percent and density had a standard deviation of less than about 3.0 percent. A summary tabulation of Davis' data is contained in Table 7.10 of the textbook by Winterkorn and Fang (1975). Reporting on a Corps of Engineers project (DeGray Dam, Caddo River, Arkansas), Strohm and Torrey (1982) presented compaction control data in general agreement with Turnbull, Compton, and Ahlvin, and with Davis. For the cohesive soils of the core and shells of the dam, and based on several hundred tests, fill water content had a standard deviation of 1.24 to 1.63 percent, while the fill compaction had a standard deviation of 2.61 to 2.87 percent. Figures 7, 8, and 9 are from the Strohm and Torrey report. They show the variation in control test data for the clay core of the dam.

Starting in the late 1950's, at the urging of the U. S. Bureau of Public Roads, there were numerous studies and reports of natural variability of compaction data on highway projects. Typical of these are Miller-Warden (1965), Redus and Spigolon (1965), Jorgenson (1969), and Essigman (1976). The reported variations for fill density had standard deviations as high as 5.5 percent with a coefficient of variation up to 5.9 percent. For water content, standard deviation values were as high as 3.6 percent with a coefficient of variation of 24 percent. The higher values, compared with the Corps of Engineers and Bureau of Reclamation data, probably represent (a) less stringent quality control measures, or (b) greater variability in borrow materials along the lengths of the highways, or (c) both.

SOURCES OF VARIABILITY

The frequency histograms of Figures 8 and 9 are illustrative of the natural variability of test data from a construction process. Similar representations can be made for measurement data for any other quality characteristic from natural or processed soil masses. Thus the need for statistical analysis as part of the geotechnical quality assurance of the construction of a hazardous waste disposal facility is clear.

A universe, or population, is defined as the totality of the set of measurements of the quality characteristic under consideration. Its

TABLE 3. VARIABILITY OF NATURAL SOIL DEPOSITS*

Parameter	Material	No. of Samples	Mean	Standard Deviation	Coeff. of Variation
Void Ratio	Gr. Sand	93	0.506	0.150	29.6
	Cs. Sand	67	0.570	0.107	18.8
	Med. Sand	38	0.686	0.128	17.5
	Fine Sand	70	0.663	0.088	13.3
	Silt	327	0.631	0.136	21.6
	Silty Clay	57	2.33	0.46	20.0
	Clay, 5 ft	120	0.900	0.157	17.5
	10 ft	96	0.911	0.138	15.1
	15 ft	47	0.909	0.186	20.4
	20 ft	21	0.749	0.236	31.6
Porosity	Gr. Sand	93	0.330	0.062	18.6
	Cs. Sand	67	0.399	0.039	9.8
	Med. Sand	38	0.404	0.041	10.1
	Fine Sand	70	0.390	0.032	8.0
	Silt	327	0.383	0.051	13.3
Specific Gravity of Solids	Silt	329	2.563	0.029	1.1
	Silty Clay	4	2.66	0.05	1.87
	Clay, High Pl.	65	2.63	0.115	4.4
	Clay, Med. Pl.	65	2.66	0.060	2.3
	Clay, Low Pl.	65	2.69	0.054	2.0
Water Content	Silt	406	0.206	0.047	22.8
	Silty Clay	790	0.84	0.19	22.0
	Clay, 4 ft	430	0.289	0.051	17.7
	10 ft	415	0.328	0.039	11.9
	16 ft	307	0.355	0.043	12.2
	20 ft	177	0.348	0.046	13.2
	Clay, 20 ft	29	0.217	0.028	12.9
	Clay, High Pl.	98	0.206	0.027	13.1
	Clay, Med. Pl.	99	0.131	0.0082	6.3
	Clay, Low Pl.	97	0.138	0.0092	6.7
Unit Weight	Clay, High Pl.	97	113.3	2.8	2.5
	Clay, Med. Pl.	99	115.8	14.2	12.3
	Clay, Low Pl.	97	112.5	2.09	1.9
Degree of Saturation	Silt	334	0.845	0.162	19.2
	Clay, 5 ft	111	0.919	0.121	13.2
	10 ft	90	0.956	0.086	9.0
	15 ft	38	0.975	0.084	8.6
	20 ft	18	0.933	0.080	8.5
Unconfined Compression Strength, tsf	Clay, 5 ft	279	2.08	1.02	49.1
	10 ft	295	1.68	0.69	40.9
	15 ft	187	1.49	0.59	39.6
	20 ft	53	1.30	0.62	47.7
	Clay	231	0.97	0.26	29.0
	Clay	97	—	—	30-40
	Clay Shale	—	—	—	37-51
	Clay Till	—	—	—	60-85
	Clay Till	—	3.24	1.17	36.1

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* Adapted from Tables 10-1 and 10-3 of Harr (1977). Data are from several published sources.

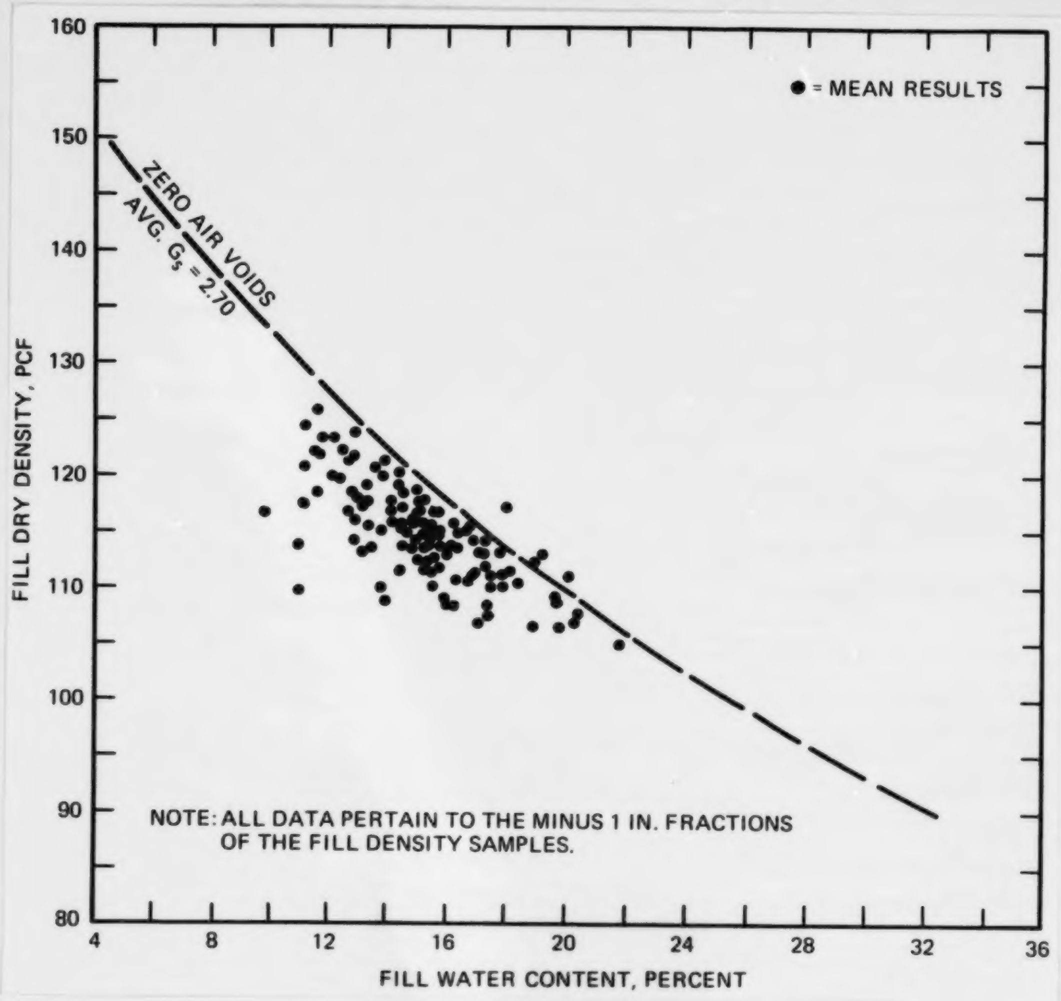
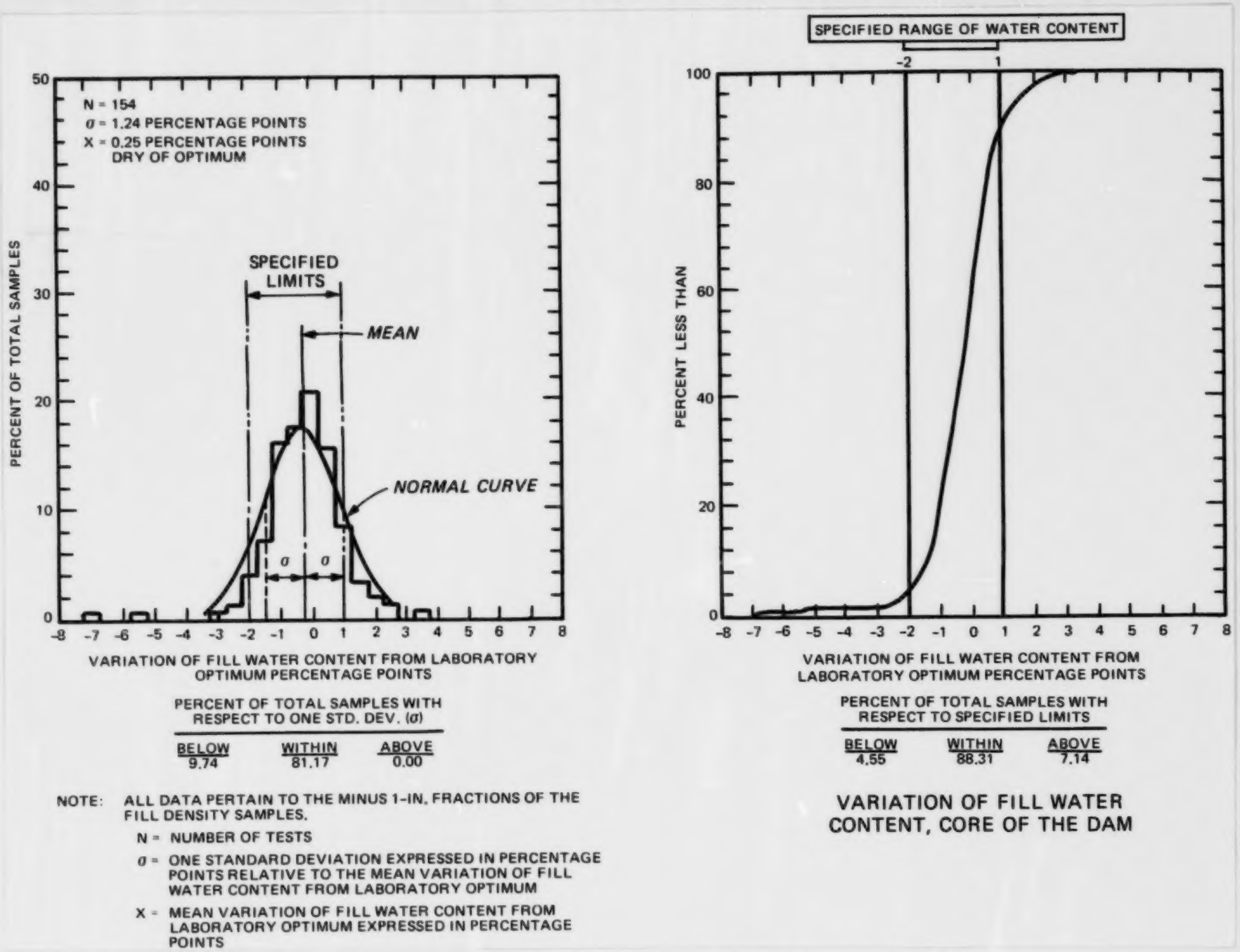


Figure 7. Results of compacted fill tests, DeGray Dam, Caddo River, Arkansas (Strohm and Torrey, 1982).



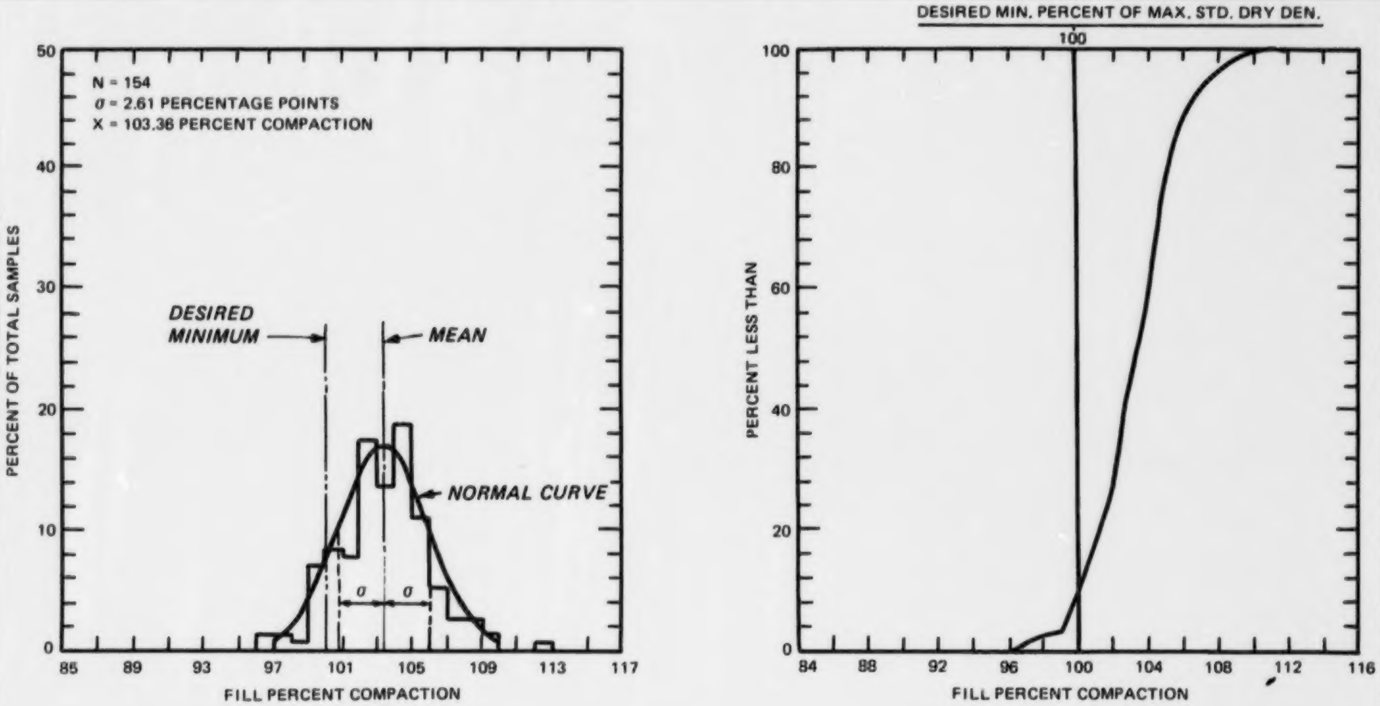
NOTE: ALL DATA PERTAIN TO THE MINUS 1-IN. FRACTIONS OF THE FILL DENSITY SAMPLES.

N = NUMBER OF TESTS

σ = ONE STANDARD DEVIATION EXPRESSED IN PERCENTAGE POINTS RELATIVE TO THE MEAN VARIATION OF FILL WATER CONTENT FROM LABORATORY OPTIMUM

X = MEAN VARIATION OF FILL WATER CONTENT FROM LABORATORY OPTIMUM EXPRESSED IN PERCENTAGE POINTS

Figure 8. Fill water content variability, DeGray Dam, Caddo River, Arkansas (Strohm and Torrey, 1982).



PERCENT OF TOTAL SAMPLES WITH RESPECT TO ONE STD. DEV. (σ)

BELOW	WITHIN	ABOVE
15.23	72.03	11.69

NOTE: ALL DATA PERTAIN TO THE MINUS 1-IN. FRACTIONS OF THE FILL DENSITY SAMPLES

N = NUMBER OF TESTS

σ = ONE STANDARD DEVIATION EXPRESSED IN PERCENTAGE POINTS RELATIVE TO THE MEAN VARIATION OF FILL WATER CONTENT FROM LABORATORY OPTIMUM

X = MEAN VARIATION OF FILL WATER CONTENT FROM LABORATORY OPTIMUM EXPRESSED IN PERCENTAGE POINTS

PERCENT OF TOTAL SAMPLES WITH RESPECT TO DESIRED % COMPACTION

BELOW	ABOVE
10.59	89.61

VARIATION OF PERCENT COMPACTION, CORE OF THE DAM

Figure 9. Fill density variability, DeGray Dam, Caddo River, Arkansas (Strohm and Torrey, 1982).

frequency distribution, usually based on a hypothetically infinite number of measurements, will typically have a form similar to that shown in Figures 8 and 9. The distribution can be characterized by a central value, the mean, and by the dispersion about that value, the standard deviation (or its square, the variance).

The numerical difference between the measured value of a characteristic and its mean, true, or reference value is termed its error. That term is used here in the statistical sense as defined and does not include error from a faulty measurement or mistake in calculation, unless the fault or mistake is included in all measurements consistently.

Variations, or errors, can be (a) random or (b) nonrandom, or (c) both. Random errors occur without aim or reason, depending only on chance. This uncontrollable variation results in measured values that are clustered about the central, mean value (Figures 8 and 9) and whose magnitude is characterized by the variance (or standard deviation) of the data. Nonrandom errors are due to some significant, assignable cause, or causes. The error cause may change abruptly, such as change from one soil type to another, or gradually, such as the spatial variation that often occurs horizontally in a soil layer. When variation occurs due to an assignable cause in a construction process, and the cause is recognized, the effect can be accounted for and often controlled.

Variation in measured characteristics of a soil mass universe stem from three causes. Williamson and Yoder (1967), Essigman (1976), and Price (1978) have described these error causes as:

a. Material composition variability

b. Placement process variability

c. Measurement process variability

Material Composition Variability

Soils are the product of degradation of rock. As stated by Peck, et al. (1974), "In a very general way, soils tend to be arranged in profiles or systems of layers. The most significant of these are profiles of weathering and profiles of deposition." Significant changes in engineering properties occur as a result of changes in soil type. Within a sample unit from a homogeneous soil mass, random variations occur because of the heterogeneity of the mineral composition of the parent rock, and because of the nonuniformity of the degradation process. Grain sizes, grain shapes, clay content, mineralogy, and nature of the pore fluid in the soil are composition variables.

Placement Process Variability

The process of placement of the soil, whether in its natural state or in a compacted fill, will result in variability in measured characteristics. Natural depositional processes tend to be uniform within a small area, such as a sample unit, or even a batch, or an entire block. However, spatial variation, vertically or horizontally, can occur gradually or abruptly as discussed above. The variations occur because of changes in the geologic processes of transportation, deposition, compaction under overburden, and erosion. In a soil of constant composition, processing affects void ratio, degree of saturation, the flocculated or dispersed structure of the clay fraction, and the shape and arrangement of pore spaces.

In earthfill operations, causes of nonrandom variations have been listed by Turnbull et al. (1966). In addition to changes in soil composition in the borrow areas, they are caused "... by changes in borrow operations, including water content adjustment, mixing and loading; by changes in operations on the fill, including number and type of hauling, spreading, and compacting equipment, water content adjustment, and placement methods; and, finally, by Nature in the form of periods of freezing temperatures, rains, and aridity in the construction area." Random variations may occur due to nonuniform coverage of the feet of a sheepsfoot roller or of the wheel prints of a rubber tired roller; or due to randomness in point-to-point lift thickness, roller speed, temperature, and water content (Essigman, 1976; Price, 1978).

Measurement Process Variability

The specific technique for a test will involve several factors. Changes in significant details of procedure, in the test technician, in technician fatigue, in instrumentation of the same kind or of different types, and in the ambient environmental conditions may cause a systematic, or bias, effect on test results. The measurement process may even be considered to include the sampling process. And therefore changes in sampling can result in nonrandom variation. Even if all other conditions are held constant, repeated tests on the same test portion by the same technician using the same equipment and procedure will result in random test values. These are caused by the unassignable and uncontrollable accumulation of small variations that are part of any testing process.

ACCURACY AND PRECISION OF MEASUREMENT

Considering the causes of variation in measurements as presented above, the topic of accuracy and precision of test methods can be discussed. In this discussion, the notations of Hald (1952) and of ASTM (1982) Designation E 177-71, "Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material", have been combined.

The measurements that constitute a sample can be combined into a group of sample statistics:

a. The arithmetic average, or mean is defined as

$$\overline{X} = \frac{\Sigma X}{n} \qquad (3\text{-}1)$$

b. The variance is

$$\sigma^2 = \frac{\Sigma(X - \overline{X})^2}{n} \tag{3-2a}$$

$$= \frac{\Sigma\varepsilon^2}{n} \tag{3-2b}$$

c. The variance may be written in an alternate form, to be used when the sample size is small (say less than n = 30), as

$$S^2 = \frac{\Sigma(X - \overline{X})^2}{n - 1} \tag{3-3}$$

d. The standard deviation is the square root of the variance.

e. The coefficient of variation expresses the standard deviation as a percentage of the mean

$$V = \frac{\sigma}{\overline{X}} \tag{3-4}$$

where X = numerical value of a measurement

n = number of individual measurements in the sample

V = coefficient of variation

Σ = mathematical symbol for summation from one to n

ε = deviation of individual measurement from the mean

Each individual measurement of a quality characteristic may be considered to be one of a hypothetically infinite number of similar measurements that could be made in a universe of the material. The difference or error between the measured value and the true or reference value is the sum of two components, an accuracy (systematic or calibration) error and a precision (random) error. This can be written as:

$$X = \mu_R + \delta + \varepsilon \tag{3-5}$$

and

$$\delta = \mu_R - \mu_P \tag{3-6}$$

where X = numerical value of a measurement

μ_R = true or accepted reference level of the property of the material to be measured

μ_P = expected value or the average of many observations recorded for the process

δ = correction for consistent or systematic error of the measurement process at the reference level μ_R

ε = correction for random deviation about the average of the observation μ_P

Accuracy refers to the degree of agreement of individual measurements or the average of a large number of measurements with a true or accepted reference value. This implies the idea of a consistent deviation, or systematic or bias error, which is a fixed or common contribution to error in each of a sample of measurements. Precision is the degree of mutual agreement among individual measurements of a consistent material made under prescribed, like conditions. The imprecision of measurement may be characterized by the standard deviation of the errors of measurement.

Accuracy Error

In Equation 3-5, the δ-term for correction for systematic, or accuracy, error is the sum of corrections from each of the three causes of nonrandom variation. This is then written:

$$\delta = \delta_M + \delta_P + \delta_T \qquad (3\text{-}7)$$

where δ_M = correction for systematic error due to material composition

δ_P = correction for systematic error due to placement process

δ_T = correction for systematic error due to testing process

Because the effects of material composition, placement process, and testing process are interrelated, it is usually impossible to differentiate these in a group of measurements. If the material composition and placement process effects are combined into a material quality effect, then:

$$\delta_Q = \delta_M + \delta_P \qquad (3\text{-}8)$$

and

$$\delta = \delta_Q + \delta_T \qquad (3\text{-}9)$$

where δ_Q = correction for systematic error of the measurement process at the reference level μ_R due to the material quality, the combined effects of material composition and placement process

The testing process accuracy correction of Equation 3-7, δ_T, can theoretically be reduced to zero for any testing process by suitable calibration. However, as stated by Willenbrock (1976, p. 18.37), "A practical difficulty in judging accuracy (of a test method) is that the only way to find the true value is by some other method of measurement. Presumably, the method employed to determine the true value should be a method of high precision that is believed to be without bias." The statistical aspects of calibration are presented later in this section of the report.

Precision Error

The precision term of Equation 3-5, ε, is a random effect, and is the combination of random effects due to the three causes discussed above. The statistical variance, σ^2, of a group of measurements of a characteristic of a consistent material using a consistent test method is the sum of the variance due to the three causes of random variability. This may be given as:

$$\sigma_0^2 = \sigma_M^2 + \sigma_P^2 + \sigma_T^2 \qquad (3\text{-}10)$$

and defining

$$\sigma_Q^2 = \sigma_M^2 + \sigma_P^2 \qquad (3\text{-}11)$$

then

$$\sigma_0^2 = \sigma_Q^2 + \sigma_T^2 \qquad (3\text{-}12)$$

where σ_0^2 = overall variance

σ_M^2 = variance due to material composition

σ_P^2 = variance due to placement process

σ_T^2 = variance due to testing process

σ_Q^2 = variance due to material quality

If the standard deviation of a particular testing process, σ_T, is known, or can be estimated, then its effect on the overall standard deviation, σ_0, can be evaluated (Hald, 1952, p 217) from Equation 3-12 as:

$$\sigma_O = \sigma_Q \sqrt{1 + \left(\frac{\sigma_T}{\sigma_Q}\right)^2} \qquad (3\text{-}13)$$

As Hald states, "On account of the uncertainty of the method of measurement, the observed values have a standard deviation that is greater than that of the true quality characteristic in question." For example, if the standard deviation, σ_T, of the testing process is equal to, or 100 percent of, the quality standard deviation, σ_Q, then the total standard deviation, σ_O, will be 41 percent larger than σ_Q. On the other hand, if the testing standard deviation, σ_T, is only equal to 20 percent of σ_Q, then the total standard deviation, σ_O, will be only 2 percent larger than the quality standard deviation, σ_Q.

When comparing alternative test methods, the effect of different standard deviations of the test methods on the overall standard deviation should be considered. For such comparisons the important conclusion that can be drawn from the examples given above and from Equation 3-13 is that when material quality is uniform (low σ_Q) the precision of the test method (σ_T) is of great importance. However, when material quality is not uniform (high σ_Q) the relative precision of one test method (σ_T) versus another is of little overall importance.

TYPES OF INSPECTION

Three major methods are available for the inspection of geotechnical construction. These are (1) screening, or 100 percent inspection; (2) process inspection (Enrick, 1972); and (3) block-by-block inspection sampling and testing.

Screening, or 100 percent inspection, is often preferred to any other type of inspection because it is the only way to be reasonably sure that all substandard aspects of the work are detected. Of necessity, the testing must be nondestructive and is usually accomplished visually. Examples are the observation of site preparation, the visual examination of the exposed surfaces of cut areas (for site media verification), and for imperfections in a geomembrane liner.

Process inspection is performed by an inspector who observes a construction process. His observations are concerned with all aspects of the work including incoming raw materials, the workmen, the equipment, and the construction process. His intent is to discover substandard construction and, when it occurs, to initiate corrective action. Examples are observations of proper equipment selection and operation, compacted lift thicknesses, and uniformity of compaction for both coverage and number of passes.

Block-by-block sampling inspection uses the result of measurements on a sample to judge the acceptability of the entire block. This method is applicable to sampling performed for either (a) process control or (b) acceptance sampling and testing. When used this method calls for a complete acceptance sampling plan. A complete acceptance sampling plan, which should be included in the design specifications, defines the following (Willenbrock, 1976; Miller-Warden Associates, 1965):

a. The quality characteristic(s) to be evaluated

b. The block size: a definite quantity of material or construction specified for acceptance or rejection

c. Location(s) of sample units or measurements

d. Number of sample units or measurements per block

e. Sampling and testing procedure

f. Method of calculation and evaluation of data; treatment of outliers

g. Acceptance criteria

h. Corrective action to be taken in the event of noncompliance

The various quality characteristics associated with geotechnical construction processes at a hazardous waste disposal facility were discussed in Section 2 of this report. Commonly used techniques for performing tests for the quality characteristics will be discussed in Section 4. The establishment of natural process tolerances and selection of acceptance criteria are both design functions, involving site-specific requirements and engineering judgment. The actual physical means of corrective action, in the case of noncompliance, is a combined design and construction operations function. Both of these latter topics are beyond the scope of this report.

A block, as defined in this report, is a definite, isolated quantity of soil, or other material, of the same composition and produced by essentially the same process. It is characteristic of a block that all measurement variation within it is random or assumed to be random, with no underlying difference between locations in the block. Therefore, the block can be characterized by a block mean and a block standard deviation for each quality characteristic. Generally, materials and workmanship close together in time or space will often be more similar than elements far apart. The size of most practical size blocks is so much greater than a sample taken from it that there is no relationship between sample size (area, volume or weight) and block size. Therefore, the size of the block is established on the basis of judgment of uniformity of materials and workmanship and on economics. (Block size selection will be discussed in detail in Section 4.) Often, this is a day's production, or a portion of a day's work, or a stockpile of material from a well defined source, or a single shipment of off-site material. For sampling, the block is usually subdivided into a large number of sub-blocks, or sampling units, each a small, easily identified length, area, volume, weight, or time period.

TYPES OF SAMPLING

Every block of material or of construction will have a frequency distribution of measurement data similar to Figures 8 and 9 for any quality characteristic. Regardless of its form, whether bell-shaped as in the given figures or in some other common shape, its quality will be characterized by a central, mean value and by random variation about the mean, defined by the standard deviation. A sample increment is a portion of material, taken from a block, for the purpose of inspection as a basis for judging, or estimating, the quality of the block. That part of a sample increment actually tested is called a test portion. The sample average is an estimator of the block average and the sample standard deviation is an estimator of the block standard deviation.

Representative Sampling

Single, representative (judgemental), sampling has been the traditional engineering approach in construction inspection, based on a deterministic attitude toward variability and the concept of the "representative" sample. Willenbrock (1976) states, "Considerations in the past to staffing, sampling, and testing time, as reflected through economics, probably guided (the traditional engineers) in this direction." Multiple sample locations, with the sample increments blended into a single test portion, have been an attempt to recognize variability and to test a sample representative of the whole, i.e., to test an "average" sample. Unfortunately, the single sample or the blending process does not yield a sampling variance by which an estimate of the block variability can be made. The judgemental selection of the sampling location(s) is usually left up to the sampler or his superiors, making the entire process dependent on the validity of his judgment, with its inherent tendency toward bias.

As stated by Deming (1950), "Judgement samples...are not amenable to statistical analysis." "...(there is) no way to remove the biases of selectivity, availability, ..., and incorrect assignment of weights." "The usefulness of data from judgement samples is determined by expert knowledge of the subject matter and comparisons with the results of previous (inspections)..., not from the knowledge of probability. Such remarks are not meant to imply that judgement samples cannot and do not deliver useful results, but rather that the reasons why they do when they do are not well understood." Judgement samples require a highly knowledgeable and experienced inspector. On the other hand, probability samples do not rely on experience or judgement of the sampler and can, therefore, be accomplished by less well trained personnel.

Random Sampling

Whether intended or not, every sample used to estimate universe, or block, parameters is a statistical sample. Its rational usefulness in this regard depends on its randomness. The requirements for a random sample, as given by Arkin and Colton (1950) are:

"1. The sample must be selected without bias or prejudice;

2. The components of the sample must be completely independent of one another;

3. There should be no underlying differences between areas from which the data are selected; and

4. Conditions must be the same for all items in the sample."

Statistical random sampling is essential for securing a sample to be used to estimate the universe mean and standard deviation of the block. Random sampling has been described by Hald (1952) in several designs:

a. Uniform random sampling

b. Stratified random sampling

c. Systematic sampling with a random start

d. Two stage sampling

Uniform Random Sampling

The uniform random sample makes every potential sampling unit in the block equally likely to be selected. A table of random numbers is used to establish the time or spatial coordinates for each sample unit. This form of sampling provides an unbiased, representative estimate of material characteristics. However, because of the small sample sizes normally used in construction inspection, such a sample may not provide the complete coverage of a block that engineering judgment demands.

Stratified Random Sampling

If a universe or block consists of, or can be divided into, a group of sub-blocks or strata having different properties according to some specified criteria, then a random sample can be drawn from each stratum instead of drawing a single random sample from the entire population. This is called stratified random sampling. The division of a soil mass or a construction process into blocks is a form of stratified random sampling. The total sample size is proportioned among the strata in accordance with their proportional weight or area. Within a single block, the time frame or the area or volume can be divided into a convenient number of sub-blocks, or sampling units, each of a size expected to yield near uniformity. These may be a square yard, or a 100 ft square, or a 15 min sequence of time. Selection of sub-blocks to be sampled, and the selection of locations within the sub-block to be sampled, are by random methods.

Systematic Sampling

A popular sampling method is systematic sampling with a random start. This method involves the selection of successive sample units at uniform intervals of time, distance, area, or volume. It is argued that if the first sample unit is selected at a random location, then all successive units are random also.

Two Stage Sampling

Two stage sampling is similar to stratified random sampling in that the block is divided into a large number of strata and a random selection is made of sample strata. Then a random sample of secondary units is selected from each primary unit. This is useful when the primary units consist of sacks, boxes, or similar containers, or the block can be arbitrarily divided as though it were similarly contained. Deming (1950) and Hald (1952) discussed this method with respect to secondary sample size as a function of the cost of securing a primary sample unit and the cost of sampling and testing each secondary unit. The greatest efficiency, assuming costs are the same, occurs in sampling only one secondary unit from each primary unit.

Example of Sampling

Probably the best method available to the engineer concerned about sampling all parts of the block is a combination of (a) stratified random sampling and (b) systematic sampling with a random start. By subdividing each block into a convenient large number of sample units, using a random start, and following a systematic pattern, a random sample with uniform coverage of the block is obtained. Hald (1952, p. 490) and ASTM (1982) Designation E 122-72, "Standard Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process", state that the number of sampling units in a block should exceed 10n, or ten times the sample size.

In random sampling, it is very useful to assign a consecutive number to every sampling unit and to select among the units by some source of randomly generated numbers. These include tables of random numbers found in many statistics textbooks or a computer generated random number series. Games of chance can be used, such as a roulette wheel or similar devices. Or a series of numbered discs, placed in a bowl and thoroughly mixed, can be used.

As an example of the various possibilities for random sampling, assume the following:

a. An inspection block consists of one area 200 ft by 300 ft.

b. The use of 10 ft by 10 ft sampling units will be employed; this gives a total of 600 sampling units with 30 rows and 20 columns in the grid.

c. The individual sampling units are numbered, in a sequential fashion, continuously from one to 600.

d. The location of the sample increment within a selected sample unit will be chosen at random.

e. The necessary sample size equals six ($n = 6$).

Then, there are several potential random sampling schemes that can be adopted for selection of sample units to be sampled:

a. Select six units completely at random from among the 600 available.

b. With a random start among the first 100 units, take every successive 100th sampling unit.

c. With a new random start among the first 100 units each time, select units at 0, 100, 200, 300, 400, and 500 added units on successive starts.

d. From every 100 successive units, select one at random.

e. Moving along the 300 ft direction, select a row in the first 50 ft at random; select a column at random. Next, select a row from the next 50 ft at random and select another column at random, etc.

SELECTION OF SAMPLE SIZE

A statistically rational and valid method for selecting sample size is given in ASTM (1982) Designation E 122-72. The equation for the number of sample units (sample size, n) to include in a sample in order to estimate, with a prescribed precision, the average of some characteristic of a block is:

$$n = (t\sigma'/E)^2 \qquad (3\text{-}14)$$

or, in terms of coefficient of variation

$$n = (tV'/e)^2 \qquad (3\text{-}15)$$

where n = number of units in the sample

t = a probability factor, from the Tables of Students'-t, based on confidence level and sample size

σ' = the known or estimated true value of the universe, or block, standard deviation

E = the maximum allowable error between the estimate to be made from the sample and the result of measuring (by the same methods) all the units in the block, i.e. the confidence interval

V' = coefficient of variation = $\sigma'/\overline{X}'$, the known or estimated true value of the universe or block

e = $E/\overline{X}'$, the allowable sampling error expressed as a percent (or fraction) of $\overline{X}'$

$\overline{X}'$ = the expected (mean) value of the characteristic being measured

The probability factor, t, in Equations 3-14 and 3-15 depends on (a) the chosen level of confidence and (b) the size of sample used to estimate σ_0'.

The confidence level is the probability that the real, but unknown, error will not exceed E or e, the confidence interval. It may be (a) one sided or (b) two sided. A one sided error concerns error in one direction only, such as below the estimated mean or above the estimated mean, where error in the other direction is of no concern. A two sided error concerns error both above or below the estimated value.

As described in ASTM (1982) Designation E 122-72, the estimated standard deviation, σ_0', should be derived from previous measurements of standard deviation for the same material or process, and should have been developed from at least 30 measurements. For each block of similar material, the new sample standard deviation can be added to the previous ones to further refine the estimate of σ_0'. If no previous data exist, σ_0' should be estimated, after which a random sample should be taken and the sample standard deviation, the square root of S^2 from Equation 3-3, should be used with an appropriate t-factor from a table of Student's-t. Tables of Student's-t factors are contained in nearly all textbooks on statistical methods, which are readily available. If the error calculated using Equations 3-14 or 3-15 is too large, then additional sample increments must be taken from that block and included with the orginal data to form a new estimate. Logically then this latter technique is the equivalent of using the first one or two inspection blocks as test sections to establish characteristics to start the project.

A tabulation of t-factors for large samples (of size, n, greater than 30) is given in Table 4. These may be used in Equations 3-14 and 3-15 where a good prior estimate of σ_0' is available.

Examples of Sample Size Selection

Two examples of sample size calculations have been developed using data from the published literature. They illustrate a one sided and then a two sided analysis.

Example 1: This is a one sided analysis. Assume that data are available to reasonably estimate σ_0' for a compacted fill process. A sample of size n tests will be randomly selected and the relative compaction percentage calculated for each test. Assume that a block average is of interest. The average percent compaction for the sample will then be used to estimate

TABLE 4. t-FACTORS FOR LARGE SAMPLES

t-Factor	Probability of Exceeding E or e* One Sided	Two Sided
3.0	0.0013	0.0026
2.575	0.005	0.010
2.320	0.010**	0.020
2.0	0.023	0.046
1.960	0.025	0.050
1.645	0.050	0.100

* E or e defined in Equations 3-14 and 3-15.

** Probability of 10 in 1000, or 1 in 100.

the average percent compaction of the construction block. Redus and Spigolon (1965) studied U. S. Army Engineer Waterways Experiment Station data on compaction of low plasticity clay, with density expressed as a percent of modified Proctor maximum density. The data yielded:

n = 172 tests

$\overline{X}$ = 91.1 percent of modified Proctor maximum

σ = 2.0 percent of modified Proctor maximum

V = 2.19 percent

Using a confidence level of 99.5 percent (a probability of 5 in 1000 that the error will exceed e), the t-factor from Table 4 is 2.575. If it is desired that the error, e, in the average not exceed 2.0 percent of modified Proctor maximum, then:

$$n = \left[\frac{2.575(2.19)}{2.0}\right]^2 = 7.95, \text{ or 8 tests}$$

Note that if the process coefficient of variation reaches 3.0 percent, then for the same confidence level and maximum error, 15 tests will be needed. If eight (n = 8) tests are used, then the maximum error in the block average becomes 2.7 percent of modified Proctor maximum density lower than the sample average.

Example 2: This is a two sided analysis. Assume that it is desired to estimate the average water content of a layer of silt soil exposed in a trench wall. The silt has previous data similar to that shown in Table 3; that is:

$n = 406$ measurements

$\overline{X} = 20.6$ percent water content

$\sigma = 4.7$ percent water content

Using a two sided confidence level of 99.0 percent (or a probability of 10 in 1000 of exceeding E) and a maximum error, E, of 5 percent water content, either above or below the sample average, then:

$$n = \left[\frac{2.575(4.7)}{5.0}\right]^2 = 5.9, \text{ or } 6 \text{ tests}$$

These tests, and those in Example 1 above, should be made on sample increments taken from their respective blocks using one or another of the random sample designs described above.

A supposed advantage of the traditional, representative sampling method is that it allows the inspection personnel to perform additional tests in an area or block of work that has been deemed critical by the design personnel. As can be seen from the above examples, the statistical sampling methods can be used by the inspection personnel to provide for such a situation. By lessening the confidence interval for a block of work, the inspection personnel are provided with more confidence in that blook of work's acceptability.

Treatment of Outlying Observations

Occasionally, in a supposedly homogeneous sample, one of the test results appears to deviate markedly from the remainder of the sample. Such an observation is called an outlier. Assuming all mistakes are eliminated, then two causes for the large deviation are of interest:

a. The outlier may be a natural occurrence of the extreme values that have a very low, but finite, probability of occurrence. In a normal distribution, such as shown in Figures 8 and 9, and using the t-factors of Table 4, a single value has a probability of 1.3 in 1000 of deviating at random for the average by 3.0 σ.

b. The outlying observation may be the result of an assignable cause, a change in universe, even though we assume it is from the same universe as the other observations.

Even though the first type of outlier is part of the random universe and should be part of the sample, it should be rejected. The sample is assumed to be representative of the universe. The presence of an outlier will sufficiently modify the sample mean and standard deviation that the sample is no longer representative and will lead to wrong decisions (Neville and Kennedy, 1964).

Criteria for rejection of outliers are based on the confidence level concepts used in Equations 3-14 and 3-15. Recommended criteria are contained in ASTM (1982) Designation E 178-80, "Standard Practice for Dealing with Outlying Observations". The procedures used in ASTM Designation E 178-80 are not difficult or complex, however, the discussion and tables included in ASTM Designation E 178-80 are too extensive to quote in this report, and the reader is referred to the document itself.

Calibration

Calibration is used to develop a relationship between the results of a testing method and a reference standard over a range of test values. Measurement of a quality characteristic can then be made using the test method and the true, or reference, value as estimated from the relationship.

The use of a calibration involves two steps. First the relationship is established, usually by a planned experiment, and a graph or mathematical equation is derived to define the relationship. Then one or more repetitions of the test method are made at a quality level, the results are averaged, and the average entered into the graph or equation to be used to estimate the true value. As will be shown below, the maximum error (confidence interval) for the true value is a function of the sample size (number of data pairs) used in the calibration experiment and of the sample size (number or repetitions) during the measurement itself.

The following discussion is limited to the use of a statistical linear regressions analysis, using the method of least squares, to fit the calibration equation to the experimental data. If the relationship is curvilinear, a similar analysis may be found in most textbooks on statistical methods and is beyond the scope of the report. A numerical example of the use of the calibration equation is given below, following presentation of the mathematical equations.

Linear Regression Analysis

The theoretical development of the method of least squares is given in most textbooks on statistical methods. These include Benjamin and Cornell (1970), Hald (1952), Miller and Freund (1977), and Neville and Kennedy (1964). The interested reader is referred to these texts for the derivations.

Linear regression analysis is used to evaluate a number of data pairs (x,y) resulting from an experiment. In calibration, this usually results from a test instrument being used to measure a range of values of a quality characteristic whose true, or reference standard, values (x) are the independent variable, while the measured values using the test device (y) are the dependent variable.

Assumptions made in linear regression analysis, using the method of least squares, are (Hald, 1952):

a. Values of x are either error free or subject to negligible error only; they can be naturally occurring or predetermined.

b. Values of y are normally distributed for all values of x.

c. The mean value of y corresponding to a given value of x is a linear function of x.

d. The random error of y (variance of y) is constant for all values of x or proportional to a given function of x. In the latter case, transformation of variables will be necessary.

For a hypothetically infinite number of data pairs for the material and test method(s) of interest, the linear relationship of y and x will be:

$$y = \alpha + \beta x + \varepsilon \tag{3-16}$$

where y = dependent variable

x = independent (error free) variable

α = intercept

β = slope

ε = random deviation in the y-direction of the y-value, at a specific x-value, from its calculated value on the line

In an experiment of finite size, the method of least squares fits the data with a straight line:

$$y = a + bx + \varepsilon \tag{3-17}$$

in which the parameters are defined by

$$a = \bar{y} - b\bar{x} \tag{3-18}$$

and

$$b = \frac{n\Sigma xy - \Sigma x\Sigma y}{n\Sigma x^2 - (\Sigma x)^2} \tag{3-19}$$

where a = intercept

b = slope

$\bar{x}$ = average of all x-values, Equation 3-1

$\bar{y}$ = average of all y-values, Equation 3-1

n = number of data pairs in sample

In many situations, particularly calibration, there is a tendency on the part of the analyst to force the data to go through the origin, i.e., $y = 0$ at $x = 0$. It is recommended that this not be done. Because of the limited size of most samples, a better fit is usually obtained by including the intercept equation (3-18). Futhermore, there may actually be a systematic error, the value of the intercept, present in all y-values, that should be recognized.

The random variability of the line is given by:

$$S_e^2 = \frac{\Sigma\ \varepsilon^2}{n - 2} \tag{3-20}$$

Recognizing that, for any given value of x, the average value of the y's is given by the estimate, $a + bx$, then:

$$S_e^2 = \frac{\Sigma[y - (a + bx)]^2}{n - 2} \tag{3-21}$$

The value, S_e, is called the standard error of estimate. The various concepts described above are presented pictorially in Figure 10.

The purpose for establishing a calibration relationship is to permit the use of measurements made using a particular device to estimate a true, or reference, value. The validity of the measurement data can be stated in terms of the maximum error, or confidence interval, that can be expected.

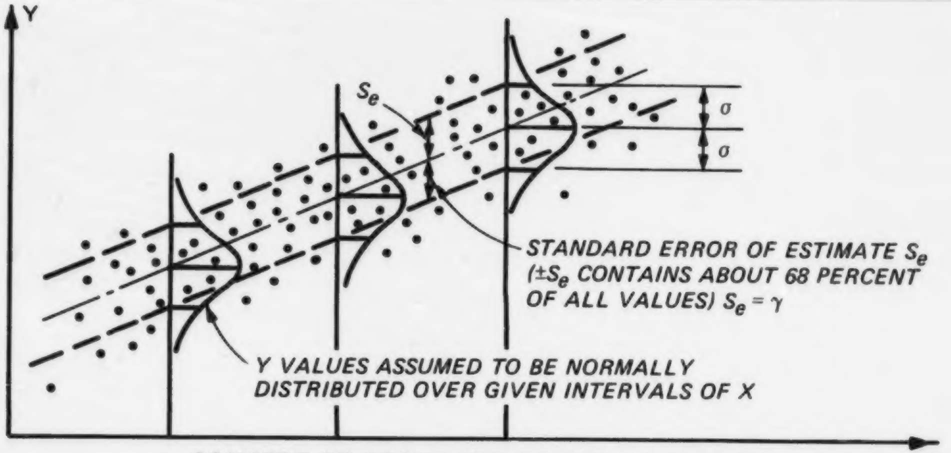
If, at a quality level $x = x_o$, the calibrated test device is used to make K repeated measurements ($K = 1,2,\ldots$) resulting in K values of y, and the y-values are averaged, yielding y', then the estimated value of x is x' given as:

$$x' = \bar{x} + \frac{y' - \bar{y}}{b} \tag{3-22}$$

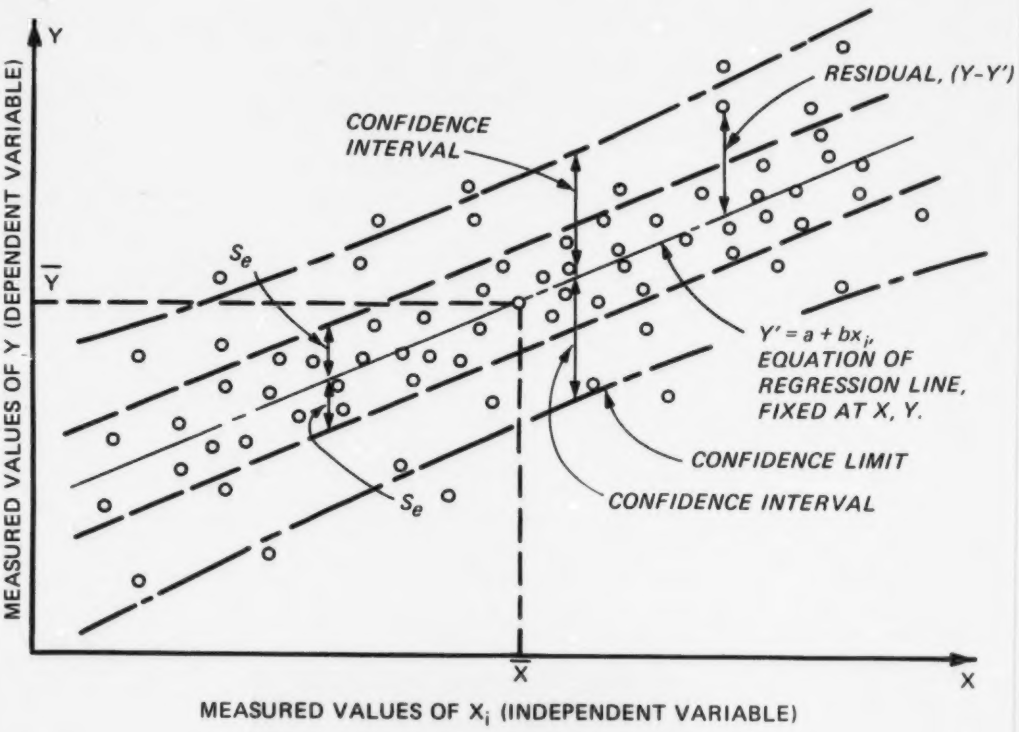
and the maximum error (confidence interval) is (Hald, 1952):

$$E(x') = t\,\frac{S_e}{b}\sqrt{\frac{1}{K} + \frac{1}{n} + \frac{[(y' - \bar{y})/b]^2}{\Sigma(x - \bar{x})^2}} \tag{3-23}$$

where y' = average of K values of y from $K = 1,2,\ldots$ repetitions of tests at the level of $x = x_o$


Y
Se
σ
σ
STANDARD ERROR OF ESTIMATE Se
(±Se CONTAINS ABOUT 68 PERCENT
OF ALL VALUES) Se = γ
Y VALUES ASSUMED TO BE NORMALLY
DISTRIBUTED OVER GIVEN INTERVALS OF X
X

a. CONCEPT OF STANDARD ERROR OF ESTIMATE



b. CONCEPT OF LINEAR REGRESSION LOAD

Figure 10. Concepts of regression analysis.

x' = estimated value of x

Using the same concept of maximum error (confidence interval) presented earlier in Equation 3-14, the term E represents the maximum deviation of the sample value from the universe value at the chosen probability level. A two sided analysis is used since it is not known if the universe value is larger or smaller than the sample estimate. The probability level, α (not to be confused with the universe intercept, α), from Table 4 should be used to define the probability that the calculated maximum error, E, will be exceeded. Values of t from Table 4 should be used for calibration experiments with over 25 data pairs. For smaller sizes (n less than 25), tables of Student's-t should be used; these are found in statistics textbooks.

The effect of sample size is reflected in the equation for maximum error (3-23). The size of the sample, n, used in the initial calibration is reflected in Equation 3-21 for the standard error of estimate and in Equation 3-23. Then the size of replicated tests, K, used when future values of x are estimated, is reflected in Equation 3-23.

The denominator within the radical of Equation 3-23 includes a term $\Sigma(x - \bar{x})^2$, which is from the initial calibration. The error in Equation 3-23 can be reduced if this term is made large. This implies that, in the planning of an experiment, such as a calibration, the x-values be chosen as far removed from the mean value, $\bar{x}$, as possible. This is preferred to the more conventional method of spacing test x-values evenly. Of course, this is also dependent on the experimenter's prior knowledge that the x - y relationship is truly linear. Even though two methods for testing for the same parameter should be related by a 45 degree line through the origin; the sample relationship, or even the universe one, may be curvilinear because of some quirk of the apparatus or technique. This factor must be considered and investigated.

Example of Calibration

The linear regression Equations, 3-16 through 3-23, given above may be applied to the evaluation of a calibration of, for example, an alternative test procedure with a standard one. Benjamin and Cornell (1970, pp. 430 - 438) presented a scattergram of data pairs representing soil water content determined on duplicate samples by the standard laboratory oven-dry procedure (Method 1 of Appendix B) and by the calcium carbide (Speedy) moisture tester (Method 5 of Appendix B). The calcium carbide method is rapid and inexpensive and is well suited to field use. The purpose of the calibration is to estimate the true, laboratory-derived water content given one or more observed values of the rapid test. In this discussion, the data are presented only for illustration and no assertion of validity is made by the authors.

Sixty-seven data pairs of water content were recorded on soil samples tested by both methods. Reversing the order used by Benjamin and Cornell, the data are identified as:

x = Laboratory oven-dry water content (independent variable), percent y = Calcium carbide (Speedy) water content (dependent variable), percent

From the listing of paired data, the following values were calculated:

a.	Sample size (number of data pairs)	$n = 67$
b.	Sum of values of x	$\Sigma x = 924.6$
c.	Sum of values of y	$\Sigma y = 924.6$
d.	Mean values of x	$\overline{x} = 13.8$
e.	Mean values of y	$\overline{y} = 13.8$
f.	Sum of squares of values of x	$\Sigma x^2 = 13{,}291$
g.	Sum of squares of values of y	$\Sigma y^2 = 13{,}260$
h.	Sum of individual x times y	$\Sigma xy = 13{,}145$
i.	Sum of squares of deviations of x	$\Sigma(x - \overline{x})^2 = 490.44$
j.	Variance of y-values about line	$S_e^2 = 3.09$
k.	Standard error of estimate	$S_e = 1.76$

The equality of the means for x and y is merely a coincidence. Using Equations 3-18 and 3-19, the best fitting straight line to the 67 data points is:

$$y = 3.79 + 0.725x \tag{3-24}$$

Equation 3-24 is theoretically valid only for the general soil type and the water content range used in the calibration. The water contents ranged from nine to twenty-three percent.

Next, assume that a sample of the same soil type is obtained, thoroughly blended, and tested K times using the Speedy moisture tester, yielding an average value, y', of 15.0 percent water content. Then, using Equation 3-22, the estimated true value (laboratory oven-dry) of water content, x', is 15.46 percent. However, this is an estimate made using a test device that is subject to random measurement error. The magnitude of the probable error in x' as a function of K, the number of repetitions of the test, can be shown by Equation 3-23.

Assume a confidence level of 0.90 and select a value of t = 1.645 from Table 4. This implies that the probability that the maximum error will be exceeded is 0.10. Then:

a. If K = 1, E(x') = 4.03 percent

b. If $K = 2$, $E(x') = 2.88$ percent

c. If $K = 4$, $E(x') = 2.08$ percent

d. If $K = 8$, $E(x') = 1.52$ percent

Therefore, if this Speedy moisture tester were to be considered an alternative to the labotatory oven-dry method, the maximum error in the estimate of x' can be reduced by repeating the test K times on the same sample of soil. However, even if K is made a large number, E(x') converges on 0.57 percent water content because of the inherent variability in the test device itself. It must also be recognized that the actual error in most tests will be much less than the maximum error.

The cost of repeated testing (K times) can, by this analysis, be compared with its benefit in a more precise estimate of x'. Given similar data for other devices, a cost comparison can then be made between the devices to provide equal precision. Furthermore, if the maximum error (confidence interval) for this test method, at a reasonable value of K, is or is not acceptable within the scope of the quality assurance requirements of the project, this factor can be experimentally established and documented as part of the total project quality assurance program record.

SECTION 4

TESTING

Section 2 of this report identified the geotechnical parameters that should be observed or tested during the construction of a disposal facility. For the purposes of this report, an observation usually does not involve a formal or specific method, whereas a test almost always involves a specific and consistent technique and often a specific piece of equipment. Standard laboratory or field test methods exist for each of the soil engineering properties and index properties that were identified and defined.

This section of the report identifies and describes the standard test methods for the soil index properties. For most of these, there exist commonly used alternative test methods; these are also identifed and described. Because observation techniques are normally nonspecific, they are described only in general terms. The merits and limitations of the various observation and test techniques, as used in a quality assurance program, are presented and discussed. None of the commonly used test methods for the same index property is clearly superior in all respects to any other test method for the same index property. It is therefore concluded that any alternative test method is acceptable, provided an acceptable calibration is made and used also.

TEST AND OBSERVATION METHODS

The following discussion includes only those tests and observations that were identified in Section 2 of this report. They are the ones considered most appropriate for both process control and acceptance inspection during construction. Although not discussed here, other tests may be used for special investigations during construction, but these are not usually performed on a routine basis. These include such tests as the engineering properties tests (see Section 2), geochemical tests, hydrology related tests, off-site evaluations of off-site materials, and material specific tests of nonsoil materials such as portland cement, asphalt, and others. The performance, recording, reporting, and evaluation of these tests should be done in a manner similar to that described below for the identified tests.

Soil Index Properties Test Methods

The listing given below includes the standard laboratory test method for each of the index properties. In most instances, alternative standard or nonstandard methods are in common use. There are undoubtedly other alternative methods for some of the tests that are used by various testing groups for construction control; however, they are not as well known, well documented, commonly accepted or as widely used as those described.

Appendix B contains a one-or-more page description of each of the test methods listed below. In each instance, the following outline has been used:

a. Parameter measured:

Title of test method:

b. Principle of test method:

c. Test method

(1) Apparatus:

(2) Procedure:

(3) Reference:

d. Limitations:

e. Status of the method:

f. Calibration procedure:

g. Documentation of test:

The various soil index properties test methods and other test methods included in Appendix B are:

Water content test

a. Standard oven dry method

b. Standard nuclear moisture-density guage method

c. Gas burner (frying pan) method

d. Alcohol burning method

e. Calcium carbide (Speedy) method

f. Microwave oven method

g. Infrared oven method

Unit weight test

a. Standard laboratory volumetric method

b. Standard laboratory displacement method

c. Standard field sand cone method

d. Standard field rubber balloon method

e. Standard field drive cup method

f. Standard nuclear moisture-density guage method

Specific gravity test

Standard laboratory method

Grain-size distribution test

a. Standard sieve analysis (+200 fraction) method

b. Amount of soil finer than No. 200 screen (wash) standard method

c. Standard laboratory hydrometer (-200 fraction) method

d. Pipette method for silt and clay fraction

e. Decantation method for silt and clay fraction

Liquid limit test

a. Standard multipoint method

b. Standard one point method

Plastic limit test

Standard laboratory method

Cohesive soil consistency test

a. Standard unconfined compression test method

b. Field expedient unconfined compression test method

c. Hand (pocket) penetrometer method

d. Handheld Torvane method

Water content/density/compactive effort tests

a. 25 blow standard Proctor compaction method

b. 25 blow modified Proctor compaction method

c. Nonstandardized Proctor compaction methods

d. Rapid, one point Proctor compaction method

e. Rapid, two point Proctor compaction method

f. Hilf's rapid method

g. Ohio Highway Department nest of curves method

h. Harvard miniature compaction method

Cohesionless soil relative density test

a. Standard laboratory maximum density method

b. Standard laboratory minimum density method

c. Modified Providence method

Geomembrane/Geotextile seam integrity tests*

a. Bonded seam strength method

b. Breaking strength method

c. Peel adhesion method

d. Air lance method

e. Vacuum box method

f. Conductivity method

Criteria for Test Method Selection

With the exception of the nuclear guage moisture-density test, the density part of volumetric field density tests, and field tests of liner materials, all of the standard test methods identified above require (a) procurement of a sample from the field and (b) performance of the test in a sheltered environment. This usually involves the availability of electric power, a water supply, freedom from dust and vibration, and a degree of control over temperature and humidity. These are conditions found in a central testing laboratory, and are available only in a few well equipped construction site laboratories, commonly found only on large construction projects. In response to this, and for the other reasons given below, alternatives to the standard test methods have come into common use for construction quality control.

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* Haxo (1981) lists potential liner materials: compacted fine grained soils, bentonite clay, asphalt, portland cement, chemical soil sealants, sprayed liquid rubbers, and geomembranes. Most construction quality tests are the same as, or closely similar to, the tests described above for soil index properties. Other, material specific observations and tests are too specialized to be included in this report. Test methods are usually available from the material supplier.

The criteria for selection among these alternative test methods include:

a. Time; speed of testing and/or speed of obtaining test results: The efficient use of men and machinery on a construction site demands that the results of quality control testing be made quickly available. Construction costs can be one or more hundred dollars per hour. As an example, the cost of a more expensive but rapid test must be compared to the total cost to the permittee of a slower test method. The time required to obtain a field sample and return it to the laboratory should be compared to the time (and cost) of a field test.

b. Accuracy and precision: A reasonable reproducibility of test results must be obtainable if the test operator or specific test equipment is changed. The accuracy must be stable so that a calibration correction can be made; and once made, can be relied on. The precision must be such that a reasonable number of tests can be averaged to yield the required maximum error (confidence interval).

c. Adaptability to field laboratory conditions: The absence of electric power, the absence of water, and/or the absence of environmental controls can effectively eliminate certain standard test techniques.

d. Adaptability to on-site use: For example, soil density is easily measured in place by the use of the mechanical or electric instruments of an undisturbed sampling method. Laboratory measurements require substantial sample manipulation and expertise on the part of the performing technician.

e. Equipment and personnel cost: A comparison can be made in terms of the capital cost of test equipment, the relative operator cost, the cost of field laboratory services, and the need for a rapid test method. Expensive, automated equipment cannot be justified if less costly apparatus will provide equivalent results in sufficient time for effective action, especially during small, slow moving construction processes.

f. Simplicity and ruggedness of equipment: An acceptable precision and sensitivity of equipment can often be achieved with apparatus that are simpler to use and more durable under field conditions than more sophisticated devices. The degree to which an operator has been trained, and his fatigue and/or boredom can seriously affect the repeatability of a test method.

g. Nondestructive testing: This is of particular importance where the act of sampling causes a discontinuity that must be repaired. For example, securing a test specimen from a geomembrane requires placement of a secure patch to maintain the integrity of the liner.

Observation Techniques

The observations identified in Section 2 are not dependent on the specifics of a particular technique. Most involve visual evaluations, or simple counting and tabulation, or are simple length or thickness measurements. The usual procedures for these observations are either straightforward, requiring no special instructions or equipment, or they involve visual comparisons that are either site specific or material specific. Therefore, any attempt to establish standardized methods would be inappropriate in this report. Specification writers and permit writers should simply state the desired end result and leave the determination of technique to the experience and ingenuity of the inspector or his supervisor.

As an example of the statements made above, the smoothness and freedom from sharp objects of the soil surface to receive a geomembrane can only be accomplished by a 100 percent visual inspection. This is also true in the observation for freedom of the placed membrane from tears. The thickness of a soil lift prior to compaction can be quickly and reasonably well checked by the performance of a number of measurements with a marked rod, or even a suitably marked spade. The observation of a freshly cut trench wall or floor starts with visual inspection for texture and color patterns, supplemented by field expedient soils tests using the visual manual procedure. Sampling and testing plans for site media verification studies can then be effectively made. The results of the observation depend more on the quality of the inspector than on any specific details of technique. Desirable qualities of an inspector are experience, integrity, technical experience and willingness.

Block Size and Testing Time

The determination of the size of a block, as stated in Section 3, is a matter of economics rather than statistical analysis. From the statistical viewpoint, the block should be sufficiently homogeneous that a reasonable number of random samples can accurately characterize its properties. From the economic viewpoint, the block size should be optimized to strike a balance between the benefits derived from continuity in the flow of construction and the benefits derived from avoiding the inherent costs of block rejection for substandard quality.

Antrim et al. (1970) discussed this matter for a fairly continuous production operation such as on a highway project. They indicate that the size of a block depends on the type of construction. Block size will be influenced by production rate, test time, and the time of analysis of data to arrive at a decision. Sampling and testing for acceptance can only be performed on the completed work, or else continued work will modify the data. Therefore, using the notation of Antrim et al. (1970) and assuming the maximum delay for a decision is equal to the time required to produce one block (unless testing is done overnight), the minimum block size is given by:

$$N = PR(\Sigma T_R + T_D) \qquad (4\text{-}1)$$

where N = number of units in block (such as square yards of fill per one lift)

PR = production rate (units/time)

ΣT_R = total test time

T_D = decision time

In Equation 4-1, the production rate is usually known and the decision time is independent of the test method used. Therefore, the economical, or efficient, block size will be a function of testing time.

From the statistical standpoint, as given in Section 3, there is no mathematical relationship between block size and n, the sample size. If it is desired that construction proceed at an unimpeded rate (assuming an alternate work location during test and decision time), then the maximum average time for an acceptance test, from Equation 4-1, is given by:

$$T_R = \frac{1}{n}\left(\frac{1}{Q_L} - T_D\right) \tag{4-2}$$

where T_R = maximum average time for a test, in hours

Q_L = production rate, in blocks per hour

T_D = decision time required to analyze data and arrive at a decision to accept or reject the block

n = sample size; the total number of test increments in the sample, from Equations 3-14 or 3-15

As an example of the use of these equations, consider the following case. The fill placement crew can place and compact about 500 cubic yards of liner soil in one half day. This is a single 6 inch lift in an area about 100 ft by 300 ft. Assuming one 500 cu yd block per 4 hours, then Q_L is 1/4 block per hour. If the conditions for Equations 3-14 or 3-15 require 8 randomly placed field density tests per block and it takes about 15 minutes to compile the data from the eight tests, analyze it, and arrive at a decision, then n = 8 and T_D = 1/4 hour. Solving Equation 4-2:

$$T_D = \frac{1}{8}\left[\frac{1}{1/4} - 1/4\right] = 0.47 \text{ hours, or } 28 \text{ min}$$

Therefore, the maximum average time for a field density test should not exceed 28 minutes. If this cannot be achieved with the test method being used, then four options are available:

a. Change to a test method that will give a testing time within the required one.

b. Lower the number of tests per block; this will have the effect of increasing the probability of exceeding the maximum error used in Equations 3-14 or 3-15.

c. Increase the size of the block, in effect reducing Q_L, the production rate in blocks per hour; then, the risk of rejecting a larger block must be justified.

d. Increase the number of crews using the test method so that average testing time will be reduced; the increased cost and the possibility of increased testing variance must be justified.

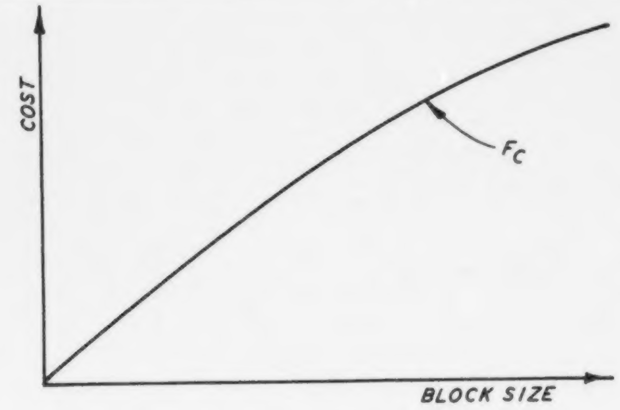
The discussion presented by Antrim et al. (1970), is of limited application in the determination of block sizes in the construction of a hazardous waste disposal facility, as Antrim et al. (1970) address considerations for a fairly continuous production rate. The construction of a hazardous waste disposal facility will probably be (a) disjointed at times and (b) lacking consistent continuity for its entire duration. Hence a more encompassing method of determining block size, one that specifically addresses the considerations for the construction of a hazardous waste disposal facility, is needed. The authors recognized this need and developed the following method.

Authors' Recommended Method for Block Size Determination

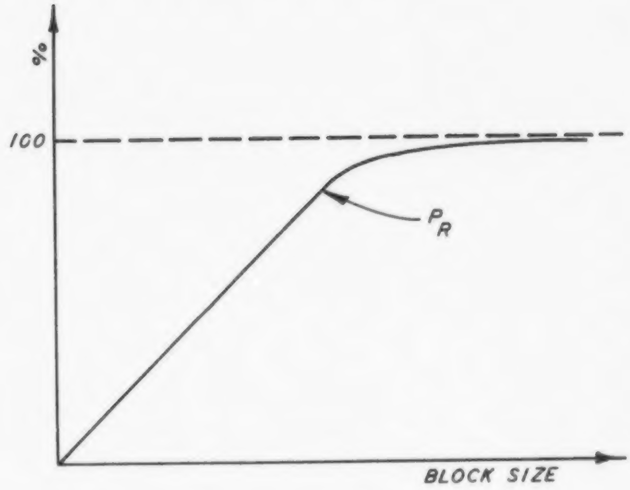
As has been stated, sampling and testing for acceptance can only be performed on completed work, for continued work on the same block will modify the data. This sampling and testing often causes interruptions in the work (See Criteria for Test Method Selection, earlier in this section). These work interruptions are necessary to assure that the designed-for standard of quality is achieved. However, given the considerable costs involved, considerable thought should be given to the schedule of these interruptions, i.e. block size.

The flow of construction is the relative continuity and larger scale operation of construction at a specific facility. This flow of construction is an abstract concept. But construction experience and the economy of scale help to illustrate this concept. Construction worker competency and task efficiency are improved through repetition. Literally, practice makes perfect. Supervisor effort can be optimized when a supervisor directs the efforts of several workers performing like tasks concurrently. It is generally more cost effective to buy and transport materials in bulk. Generally, rental costs per item of equipment lessen as the amount of equipment, rented at one time from the same outlet, increases. Conversely, worker attention and task efficiency suffer from frequent work stoppages. The frequent cranking on and turning off of equipment wears heavily on that equipment. Peacemeal procurement practices are generally cost ineffective. There are innumerable other examples to illustrate the concept. They all serve to show that the permittee can reap economic benefit from enhancing the flow of construction. This flow of construction and the economic benefit derived from its enhancement are depicted in Figure 11.

Given that the benefit of enhancing the flow of construction has been presented, it should be clearly stated that the designed-for standard of quality must be achieved everywhere and never compromised. From an economic viewpoint, these two motivators: (1) enhancing the flow of construction



This curve reveals the economic advantage of increasing the block size. The curve can generally represent the plots for the values of C_W, C_I, C_C, C_L, C_X, C_R or F_C.



This curve shows that for block size independent sampling, P_R increases almost linearly till it approaches the 100% line.

Figure 11. Graphic representation of important values for the authors' recommended method

and (2) achieving the standard of quality, appear to be conflicting. However a compatible balance can be struck between them, and this is the object of the authors' method.

The following points form a necessary preface to the presentation of the authors' method:

a. For any given construction process there may be one or more quality characteristics to be verified, i.e. sampled and tested.

b. A block size must be sufficiently large to allow statistical sampling, as per Section 3, to verify each quality characteristic within the block.

The following values are defined as indicated:

a. C_W This is the cost of the materials and workmanship that go into the effort of construction. (Wherever it is used the word cost means all the costs involved, i.e. including time, money and intangibles such as the loss of worker attention.)

b. C_I This is the cost of inspection, that is the cost of the quality inspection plus the cost entailed in the stoppage of construction in order to accomplish the inspection. The cost of inspection can also be considered the worth of inspection. This is because a block of construction, for which a quality inspection has been performed, is intrinsically of more value to the permittee than was that same block of construction before the inspection was performed.

c. C_C This is the total cost of construction, that is the cost of the materials and workmanship plus the cost of inspection, so:

$$C_C = C_W + C_I \tag{4-3}$$

d. C_L This is the cost of the lost materials, workmanship and inspection when a block of work is rejected, so often:

$$C_L = C_{W1} + C_{I1} = C_{C1}{}^{*} \tag{4-4}$$

e. C_X This is the cost of removing a block of construction.

f. C_R This is the cost of rejection, that is the total cost when a block of work is rejected, so:

$$C_R = C_L + C_X + C_{C2} \tag{4-5}$$

g. P_R This is the probability that a block will be rejected. The probability of rejection can only be estimated by the permittee's forces. They must use all their experience, particularly the on-site experiences of the inspectors, to estimate P_R. The value of P_R used should be the probability that any quality characteristic tested will be found unacceptable. The addition law of probability should be used to calculate the probability of non-acceptance for a group of quality characteristics to be verified.

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* The number 1 indicates that this was the first time this work was accomplished. Naturally, the number 2 indicates the second time.

h. D_R This is the deterrent or risk of rejection, that is the probability of rejection times the cost of rejection, so:

$$D_R = P_R C_R \tag{4-6}$$

i. BS_O This is the optimal block size.

j. BS_S This is the minimum block size possible which allows statistical sampling of each quality characteristic within the block. To determine this value, one must first determine a minimum block size for each quality characteristic within the block. Then from among these minimum block sizes the largest is chosen to represent the BS_S for the entire block. This entire determination will usually be a moot effort as will be discussed later.

k. F_C This is the flow of construction, an abstract concept defined earlier.

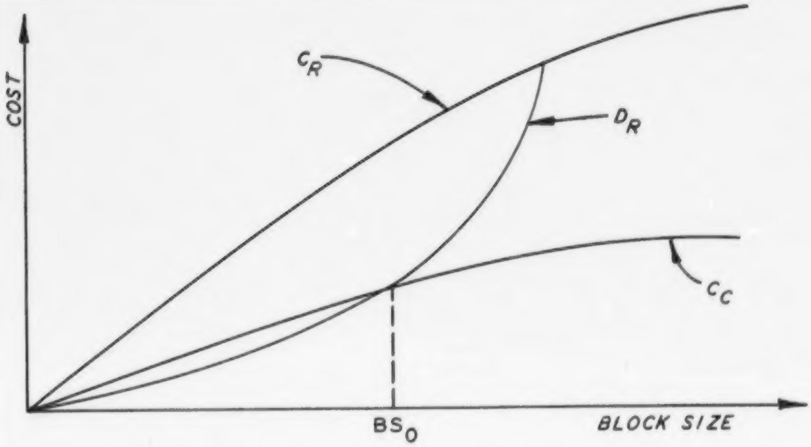
An elementary risk analysis, as depicted by Figure 12, shows that the optimal block size is located where the cost of construction exactly equals the risk of rejection, so:

$$BS_O \;@\; C_C = D_R \tag{4-7}$$

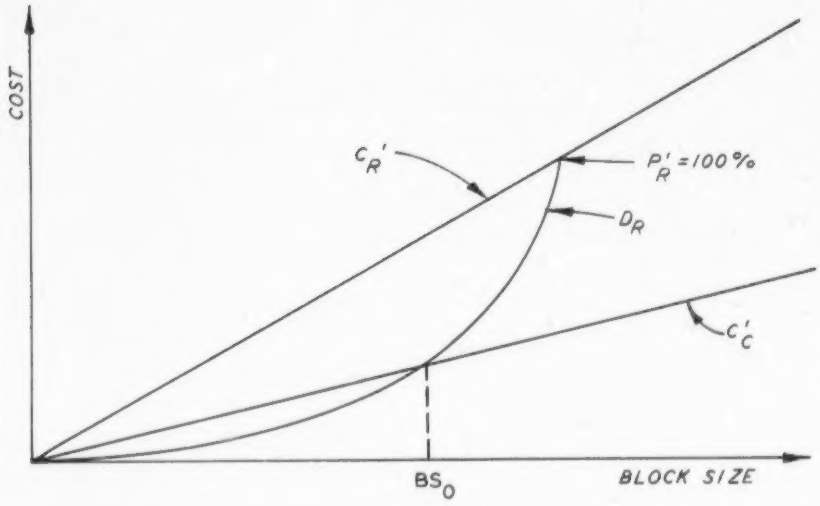
And if the value of BS_O exceeds the value of BS_S then the value yielded by Equation 4-7 is the block size the permittee should use for economic optimization while assuring quality. (This will almost always be the case. The authors can only conceive of extremely rare instances when BS_O might not exceed BS_S. Conversely, it is more likely that BS_O will exceed the maximum block size which still allows inspection. In this event the statistically valid, maximum block size becomes BS_O. An example of this event would be the compaction of earthfill over a very small trench. Each lift, or completed block of work, must be inspected before the next lift can be compacted.) If BS_O does not exceed BS_S, then BS_S is the block size the permittee should use to assure quality.

It should be noted that if the permittee's forces miss in their estimate of P_R, their miss will manifest itself. The economic motivators of enhancing the flow of construction and minimizing the cost of block rejection will encourage the permittee's forces to redetermine a value for P_R, yielding a new block size closer to the optimum.

Experienced construction supervisors might be tempted to reject this



There can exist a point at which an increase in the block size means that inspection (sampling and testing) can no longer be performed. This discontinuity is not represented in the figure for the sake of simplicity.



The relationship between the values can be better visualized if the values for C_C, C_R, and P_R are assumed to be linear, i.e. C_C', C_R', and P_R'. Note that once P_R' equals 100%, $D_R = C_R'$.

Figure 12. Graphic representation of the solution of BS_O

method as too complicated. In fact it is not. In fact it delineates clearly what many construction supervisors attempt to do in their head. It also calls for their experience in the estimate of P_R. The other values needed are readily determined. And the method serves to minimize the effects of human error.

Once BS_O has been determined for a given construction process, then it is a logical next step to determine the total number of blocks to be inspected for that particular process. In this way this method also helps both the construction and inspection groups organize their effort.

Examples of the Authors' Recommended Method

The following examples demonstrate the utility and flexibility of the authors' recommended method.

a. Example 1. At a given hazardous waste disposal facility one of the landfill units has been filled with waste. The earthfill over the waste must be compacted preparatory to the construction of a trench cover. The trench itself is 500 ft by 200 ft.

The compaction crew supervisor knows that it costs approximately $2.20 per cubic yard of compaction. This cost includes the costs of the compaction equipment and its fuel, the labor costs of the compaction crew and the quality assurance inspectors observing the compaction, and all associated costs.

The compaction crew supervisor knows the cost of removing a lift of compacted earthfill. Should the quality assurance inspectors find a lift of compacted earthfill to be unacceptable and should those same inspectors determine, along with the supervisor, that the lift must be removed, it will cost approximately $1.50 per cubic yard.

The compaction crew supervisor also knows that in a given nine hour day, with about an hour off for lunch and breaks, that his crew can compact about 1,000 cubic yards. He also knows that lengthy stops for his crew hinders their efficiency. It takes them time to get back to their normal work rate.

The two quality assurance inspectors know that they cost approximately $30 per hour, as a team, to perform their sampling, testing and evaluation of a completed block of compacted earthfill. They also know that it takes each of them approximately 15 minutes to take, test and evaluate a given sample.

The quality assurance inspectors use a statistically valid, random sampling method (as described in Section 3) to determine the sample size for the completed block of compacted earthfill to be tested. The sample size is eight.

The quality assurance inspectors know the importance of their work. They also understand the concerns of the compaction crew supervisor.

They decide to work with the supervisor to find the optimal block size.

The inspectors and supervisor know from previous experience, and from the trend that has been established at this hazardous waste disposal facility, that one unacceptable test result is found for every 250 cubic yards of compacted earthfill. They also decide that, given the authors' recommended method, the work stoppage factor with which the supervisor is very familiar will be given a value of 1.2.

The following list summarizes what the quality assurance inspectors and the compaction crew supervisor feel are the appropriate values to be used in the authors' recommended method.

(1) Compaction costs = \$2.20/yd^3

(2) Removal costs = \$1.50/yd^3

(3) Compaction crew rate = 1000 yd^3/day or 125 yd^3/hr

(4) Number of inspectors = 2

(5) Sampling costs = \$30/hr

(6) Sampling time = 15 min/sample or .25 hr/sample

(7) Sample size = 8 samples

(8) Probability of unacceptance = 1/250 yd^3

(9) Work stoppage factor = 1.2

The following values were defined earlier in the presentation of the authors' recommended method. Here they are shown in terms of their units of measure:

$$C_W = \left(\frac{\text{cost of construction}}{\text{unit}}\right) \times (\text{block size in units})$$

$$C_I = \left[\frac{(\text{sample size}) \times (\text{time/sample})}{(\text{number of inspectors})} = \text{total samplling time}\right] \times \left(\frac{\text{sampling costs}}{\text{time}}\right)$$

$$+ \left[(\text{work stoppage factor}) \times \left(\frac{\text{cost of construction}}{\text{rate of construction}}\right) \times (\text{total sampling time})\right]$$

$$C_X = \left(\frac{\text{cost of removal}}{\text{unit}}\right) \times (\text{removal size in units})$$

$$P_R = \left(\frac{\text{estimate of unacceptable test results}}{\text{unit}}\right) \times (\text{block size in units})$$

Replacing the word descriptors with variables and actual working units reduces these definitions, or equations, to the following:

$$C_W = \left(\frac{\$a}{\text{unit}}\right) \times (\text{b units}) = \$(a)(b)$$

$$C_I = \left[\frac{(\text{c samples})(\text{d hrs/sample})}{(e)} = (\text{f hrs})\right] \times \left(\frac{\$g}{\text{hrs}}\right)$$

$$+ \left[(h) \times \frac{(\$a/\text{unit})}{(\text{j hrs/unit})} \times (\text{f hrs})\right] = \$(f)(g) + \frac{\$(h)(a)(f)}{(j)}$$

$$C_X = \left(\frac{\$k}{\text{unit}}\right) \times (\text{m units}) = \$(k)(m)$$

$$P_R = \left(\frac{n}{\text{units}}\right)(\text{b units}) = (n)(b)$$

The quality assurance inspectors and the compaction crew supervisor can solve for their optimal block size by assigning the above variables the values upon which they agree:

(1) $a = \$2.20/\text{yd}^3$

(2) b = optimal block size

(3) c = 8 samples

(4) d = .25 hr/sample

(5) e = 2

(6) g = $30/hr

(7) h = 1.2

(8) $j = 1\ \text{hr}/125\ \text{yd}^3$

(9) $k = \$1.50/\text{yd}^3$

(10) m = b*

(11) $n = 1/250\ \text{yd}^3$

---

* The quality assurance inspectors and the compaction crew supervisor know that statistical validity dictates that an unacceptable test result will mean complete block removal.

Given these values the following equations result:

$$C_W = \$(a)(b) = \$2.20(b)$$

$$C_I = \$(f)(g) + \frac{\$(h)(a)(f)}{(j)}$$

$$f = \frac{(8)(.25)}{(2)} = 1 \text{ , so}$$

$$C_I = \$(1)(30) + \frac{\$(1.2)(2.20)(1)}{(.008)} = \$30 + \$330 = \$360$$

$$C_X = \$(k)(m) = \$1.50(b)$$

$$P_R = (n)(b) = 0.004(b)$$

Now the optimal block size can be determined:

$$C_C = C_W + C_I \qquad (4\text{-}3)$$

$$C_C = \$2.20(b) + \$360$$

Given the assumption that an unacceptable test result means complete block removal or loss:

$$C_L = C_{C1} \qquad (4\text{-}4)$$

$$C_L = \$2.20(b) + \$360$$

$$C_R = C_L + C_X + C_{C2} \qquad (4\text{-}5)$$

$$C_R = \$2.20(b) + \$360 + \$1.50(b) + \$2.20(b) + \$360$$

$$C_R = \$5.90(b) + \$720$$

$$D_R = P_R C_R \qquad (4\text{-}6)$$

$$D_R = .004(b)[\$5.90(b) + \$720]$$

$$D_R = \$.0236(b)^2 + \$2.88(b)$$

$$BS_O \text{ @ } C_C = D_R \tag{4-7}$$

$$\$2.20(b) + \$360 = \$.0236(b)^2 + \$2.88(b)$$

$$2.20(b) + 360 = .0236(b)^2 + 2.88(b)$$

$$0 = .0236(b)^2 + .68(b) - 360$$

Using the quadratic equation to solve for b, the unknown value, equal to the block size:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$b = \frac{-.68 \pm \sqrt{(-.68)^2 - 4(.0236)(-360)}}{2(.0236)}$$

$$b = \frac{-.68 \pm \sqrt{.4624 - (-33.984)}}{.0472}$$

$$b = \frac{-.68 \pm 5.869}{.0472}$$

Solving for the real solution gives:

$$b = BS_O = 109.9 \cong 110 \text{ yd}^3$$

So in order to optimize the flow of construction while assuring the standard of quality, the compaction crew should compact 110 cubic yards of earthfill at a time before stopping to allow the quality assurance inspectors to conduct acceptance testing.

b. Example 2. Assume that the quality assurance inspectors and the compaction crew supervisor in Example 1 are very confident that they will always achieve a moisture content in their compacted earthfill at or very close to the optimum moisture content. Assume that it follows that they believe the only remedial action they will require in the event of an unacceptable test result will be the application of more compactive effort. Thus the inspectors and supervisor conclude that they will never have to remove a block of compacted earthfill in the event of non-acceptance.

From experience, and from the trend established at the facility, the inspectors and the supervisor decide that the time required for the typical number of remedial compactive effort passes is approximately one half hour per 200 cubic yards of compacted earthfill involved.

Thus the changed values from Example 1 are:

$C_X = 0$

$C_L = 0$

C_{C2} = [(remedial compactive effort rate: hr/yd^3)

× (remedial compactive effort cost: \$/hr)

× (block size: yd^3)

= (total remedial compactive effort cost: \$)] + C_I

The remedial compactive effort takes one half hour per 200 cubic yards. So the remedial compactive effort rate is 400 yd^3/hr or .0025 hr/yd^3.

The remedial compactive effort cost will be nearly the same as the compaction cost, since all the same personnel and equipment are involved. The compaction cost is \$2.20/yd^3. The compaction crew works at the pace of 125 yd^3/hr. So their per hour cost, and that which we estimate the per hour cost of the remedial compactive effort to be, is \$275/hr.

Thus C_{C2} can be solved for in terms of b, the unknown block size:

$$C_{C2} = \left(\frac{.0025\ hr}{yd^3}\right) \times \left(\frac{\$275}{hr}\right) \times (b\ yd^3) + C_I$$

$$C_{C2} = \$.6875(b) + \$360$$

Now the optimal block size, BS_O, can be found:

$$C_R = C_L + C_X + C_{C2} \qquad (4\text{-}5)$$

$$C_R = C_{C2} = \$.6875(b) + \$360$$

$$D_R = P_R C_R \qquad (4\text{-}6)$$

$$D_R = .004(b)[\$.6875(b) + \$360]$$

$$D_R = \$.00275(b)^2 + \$1.44(b)$$

$$BS_O @ C_C = D_R \tag{4-7}$$

$$\$2.20(b) + \$360 = \$.00275(b)^2 + \$1.44(b)$$

$$0 = \$.00275(b)^2 - 0.76(b) - \$360$$

$$0 = .00275(b)^2 - 0.76(b) - 350$$

Solving for b, the unknown optimal block size, by the quadratic equation yields:

$$BS_O = 525 \text{ yd}^3$$

As was stated in Example 1, the trench size is 500 ft by 200 ft. If the compaction crew is compacting in 6 inch lifts, then one lift over the entire trench would be 5,556 cubic yards of fill. Thus there should be 10.6, or approximately 11, blocks of compacted earthfill in every lift over the entire trench.

c. Example 3. A geomembrane will be installed as part of the cover for the trench being filled in Examples 1 and 2. The inspector and the geomembrane installation supervisor determine the following values:

(1) Sample size = 18 samples

(2) Sampling time = 15 min/sample or .25 hr/sample

(3) Number of inspectors = 1

(4) Sampling costs = \$12/hr

(5) Seam bonding costs = \$45/hr

(6) Seam bonding rate = 8 ft/hr (initial QC is performed in conjunction with the installation)

(7) Repair costs = \$45/hr

(8) Repair rate = 30 min/ft or .5 hr/ft

(9) Seam = 700 ft

Thus the following values can be assigned:

(1) $a = \left(\frac{\$45}{\text{hr}}\right)\left(\frac{\text{hr}}{8\text{ ft}}\right) = \$5.63/\text{ft}$

(2) b = optimal block size

(3) c = 18 samples

(4) d = .25 hr/sample

(5) $e = 1$

(6) $g = \$12/\text{hr}$

(7) $h = 1.2$ (again)

(8) $j = 1\ \text{hr}/8\ \text{ft} = .125\ \text{hr}/\text{ft}$

(9) $k = \left(\frac{.5\ \text{hr}}{\text{ft}}\right)\left(\frac{\$45}{\text{hr}}\right) = \$22.50/\text{ft}$

(10) $m = b$

(11) $n = 1/29\ \text{ft}$

Given these values the following equations result:

$C_W = \$(a)(b) = \$5.63(b)$

$C_I = \$(f)(g) + \frac{\$(h)(a)(f)}{(j)}$

$$f = \frac{(18)(.25)}{(1)} = 4.5, \text{ so}$$

$C_I = \$(4.5)(12) + \frac{\$(1.2)(5.63)(4.5)}{(.125)} = \$54 + \$243.22 = \$297.22$

$C_X = 0$

$P_R = (n)(b) = .0345(b)$

Now the optimal block size can be determined:

$$C_C = C_W + C_I \tag{4-3}$$

$$C_C = \$5.63(b) + \$297.22$$

$$C_L = 0$$

$$C_{C2} = (k)(m) + C_I = \$22.50(b) + \$297.22$$

$$C_R = C_L + C_X + C_{C2} \tag{4-5}$$

$$C_R = \$22.50(b) + \$297.22$$

$$D_R = P_R C_R \tag{4-6}$$

$$D_R = .0345(b)[\$22.50(b) + \$297.22]$$

$$D_R = \$.776(b)^2 + \$10.25(b)$$

$$BS_O \ @\ C_C = D_R \tag{4-7}$$

$$\$5.63(b) + \$297.22 = \$.776(b)^2 + \$10.25(b)$$

$$0 = .776(b)^2 + 4.62(b) - 297.22$$

Solving for b, the unknown block size, yields:

$$BS_O = 16 \text{ feet } 10 \text{ inches}$$

So there will be approximately 42 blocks of work in the bonding of the 200 ft seam of geomembrane.

COMPARISON OF ALTERNATIVE TEST METHODS

The following discussion of the merits and limitations of the test methods listed earlier relates primarily to the construction operations at a hazardous waste disposal facility. All of the considerations presented here with regard to standard test methods, alternate test methods, sampling, calibration, and relative merits are applicable regardless of the mechanism of the quality assurance program being employed.

Alternatives to the standard test methods may be acceptable if:

a. They measure the same fundamental property as the standard method; or they correlate well with the standard test results.

b. There is a consistent relationship with the standard, i.e., a consistent bias or accuracy error or constant calibration error.

c. The test precision is constant, and is known or may be estimated, so that the maximum random error of a single or replicated test may be evaluated.

Water Content Test Methods

Three different methodologies are in common use to determine the water content of a soil during construction control:

a. Drying methods: These involve the removal of free water by a drying process and comparing the weight loss, presumed to be water, with the dry weight of the soil. The methods include standard oven drying to constant weight at 105°C, pan drying over a flame or other heat source, drying by use of hot air, drying by an infrared radiation source, or drying by a microwave oven. The alcohol burning method uses the heat, from the burning of alcohol added to the soil, to dry the soil.

b. Chemical methods: The most popular of these is the Speedy moisture method using calcium carbide. The chemical is added to the wet soil in a closed container and the pressure of the acetylene gas which is produced is proportional to the free water present.

c. Nuclear methods: The nuclear moisture-density guages are commonly used on projects of all sizes. They rely on neutron thermalization to indicate hydrogen content.

A number of comparative evaluations of water content test methods have been published. They include Shaw and Arble (1959), Johnson and Sallberg (1960), Schwartz (1967), Antrim et al. (1970), Smith (1970), and Schmugge, Jackson, and McKim (1980). All are in general agreement in their evaluations.

Oven drying to constant weight at 105°-110°C is the long-accepted standard method, using a controlled temperature oven. However, Lambe (1951) reports experimental data to show that typical laboratory ovens are nonuniform in temperature and will give slightly variable water content results. A study by the Waterways Experiment Station (USAE, WES, 1954) showed that, for soils containing gypsum, some of the bound water is evolved at temperatures below 105°C, affecting the results.

The distribution of water content throughout a soil sample is generally nonuniform because of the nonuniformity of the percent fines, particularly percent clay sizes, throughout. In a density sample of 2000 to 3000 grams total weight, there are a number of 100 gram water content samples that can be tested by the oven drying method. Unless the soil is thoroughly blended, the average water content will not be measured by the small sample. If water content is used to establish the dry density of a sample, then the entire sample should be dried; this then requires a large oven if a number of density tests are to be made in one day.

All alternative water content test methods require calibration with the standard oven dry method. The criteria given above require a stable calibration; this usually requires a consistent test technique.

The gas burner (frying pan) method uses an uncontrolled temperature to dry the soil, with temperature often above 110°C. The Waterways Experiment Station (USAE, WES, 1954) report showed that wide variation in temperature above 110°C had negligible effect on low plasticity soils and only moderate effect on medium plasticity soils. However, because the temperature is uncontrollable, the results are likely to be highly variable. The maximum errors should be small at low water content, resulting in small errors in associated values such as dry density or the Atterberg limits. The gas burner method requires shelter, but no electricity or water.

The infrared radiation, hot air blower, and microwave oven methods offer some improvement over the gas burner method, but they require electricity in addition to shelter. The testing time can be controlled and the test apparatus standardized, offering the possibility of more stable calibration.

The alcohol burning method has a safety hazard in the open flame resulting from the combustion of the alcohol-soil mixture. All of the comments given above for the gas burner method apply to this method. It also requires a source of expendable alcohol. Since this method has no advantage over the gas burner method, and is more unstable in calibration than the various cooking methods, its use cannot be recommended. It is no longer commonly used on construction projects.

All of the methods described above require testing times of 30 minutes to several hours, with the exception of the microwave oven. This is a distinct advantage over standard oven drying which requires eight to 24 hours to reach constant weight. Unless, of course, the time delay does not measurably delay the construction operation.

All of the drying methods require that the soil test portion be brought in from the field and dried in a protective shelter. This requires manpower time for travel and causes the test technician to be away from the construction site. The calcium carbide (Speedy) method is adaptable to on-site testing, particularly if the shelter of a vehicle is available for the weighing of the 26 gram sample of wet soil. The entire test can be completed in ten minutes or less. The cost of the apparatus is a few hundred dollars and the expendable calcium carbide costs only a few cents per test. Schwartz (1967) reported a calibration standard error (Equation 3-20) of 1.44% water content, so that most test values should be within one percent of the oven dry water content. The apparatus is rugged and well adapted to field operation. Since there is no appreciable heat evolved and only the free water combines with the calcium carbide, the presence of organic matter and/or gypsum is not of concern, as it is in the drying methods. However the small sample size, 26 grams, limits the method to fine grained soils. Also, the soil must be thoroughly blended if the small sample is to be representative of the average water content of a larger soil test increment.

The nuclear moisture-density apparatus costs several thousand dollars and can be used for both water content and density tests in the field. Four to six moisture-density tests can be performed continuously per hour by one man. The tests are nondestructive and, therefore, can be repeated as a replication or as a check for consistency. The tests can be made on any flat surface, whether horizontal or inclined. Although the present day instruments are fairly rugged, the electronic components have some drift, requiring periodic recalibration. Because the guage responds to all hydrogen present, including that in organic material and crystalline water, it is necessary that a field calibration check be frequently made against oven dried soils. Under normal operating conditions, the instrument poses no health hazard. However, formal operator training and a state license are normally required.

In summary, all of the methods discussed above are viable, reasonable alternatives to the standard oven drying method, provided, of course, that there can be a consistent calibration with acceptable precision. In operations where the moisture content samples can be obtained during the day's work, and dried in the oven overnight, only a minimum of technician time will be required; and the oven drying method can be recommended.

The alternative drying methods require 30 minutes to a few hours of drying time for a single sample or a small group of samples. This time requirement of an inspector/technician would make him unavailable for field observations, thus possibly requiring an additional inspector. This is undesirable, for labor is by far the highest cost item in inspection. Therefor, unless the work schedule is so slow and intermittent that one inspector can perform the field observations and also devote considerable time to laboratory tests, the drying methods cannot be recommended.

The calcium carbide (Speedy) method may be used in the field or in the laboratory, with results obtained in 5 to 10 minutes. It is applicable to nearly all the soil types that would be encountered at a disposal facility. With this method, thorough mixing of the soil is necessary to obtain a meaningful representative test portion of 26 grams.

The nuclear moisture-density guage can only be used in the field on a large soil mass. Small laboratory samples from Atterberg limits testing or from compaction tests cannot be tested with this device.

Both devices, the Speedy and the nuclear guage, are sufficiently rapid that the inspector can use them for process control and for acceptance testing without adversely affecting construction efficiency. They are therefore recommended for inspection testing intended to enhance the flow of construction.

Unit Weight (Density) Test Methods

The two laboratory methods for unit weight tests, volumetric and displacement, are not generally considered process control tests. Both are time consuming and require a laboratory environment.

In the volumetric method, the careful trimming of a soil mass into a container of known volume or to a specific cylindrical diameter in a soil lathe, or careful coverage with parafin or wax, requires skilled laboratory technicians. The volumetric method is often used to prepare specimens for other tests, such as unconfined compression tests or laboratory permeability tests to be made on larger undisturbed field specimens or specimens of compacted soil prepared in larger molds.

A large number of studies evaluating field density test methods have been published, mainly in the journals of highway engineering. Typical of these are the papers by Johnson and Sallberg (1960), Schwartz (1967), Winterkorn and Fang (1975), and Antrim et al. (1970).

The four most widely accepted field density test methods are used primarily for compaction evaluation. Three are direct techniques involving removal of soil from the test site, weighing the removed soil, and measuring the volume of the hole. These three: sand cone; water balloon; and drive cup; differ only in their methods for measuring hole volume.

The sand cone method depends on a calibrated sand density developed by dropping through the valve of the apparatus cone. Unless the hole depth is constant and the same as that used for calibration, a small bias error is introduced. Vibration of the site by nearby construction machinery can densify the sand during the test, introducing another possible error. The sand is generally not reusable, requiring frequent resupply. A balance, of sufficient capacity for weighing the sand filled apparatus, is needed. This balance is usually different than the smaller balance used for the moisture content tests by drying. The sand cone method can be used for the full range of soils expected at a disposal site.

The rubber balloon method measures the hole volume by the forcing of a water filled rubber balloon into the hole, with an apparatus used to measure the change in water volume. As long as sharp stones or pieces of wood or roots are not encountered, the balloon has a reasonable service life in spite of its thinness and flexibility. The water and rubber balloon are sucked out of the hole and reused, obviating the need for resupply. The rubber balloon system will fit any hole well unless the hole is highly irregular in shape or unless it contains root matter. In these latter two instances an error of significant magnitude can be created.

In the drive cup method, a thin walled, steel tube is driven into the soil. The soil must be fine grained and sufficiently yielding so that the tube is not distorted. The soil filled tube is then dug out of the ground, its ends are carefully trimmed, and it is weighed. With the volume of the tube known, the soil density can be calculated. This method cannot be used in sand, or in a soil containing stones. Another potential source of error results when the soil is slightly compressed by the volume of the steel tube walls and the wall friction developed during sampling.

All three of the direct methods discussed above require two steps: (1) the hole is dug or the tube driven and removed; then the volume of the soil is measured; and (2) the soil removed from the hole is weighed and the wet density, or weight per unit of volume, is calculated. The determination of the soil's dry density requires that the water content be determined by one of the methods described earlier. In acceptance testing of a construction block, such as for a lift of fill, a number of density tests are performed at one time. This allows a partitioning of the work. All the field work can be performed at one time. This is then followed by a transport of the protected samples to the field laboratory for their weighing and subsequent moisture determination. This method becomes cumbersome for process control work when only one or two tests can be made at a time. In this situation, all the weighing and moisture determination should be performed on site, or else there will be a loss of time, and a loss of inspector observation capability while he is working in the laboratory. Each of these test methods requires 15 to 45 minutes of field work, followed by additional laboratory time. A skilled technician can perform eight to ten tests, density and water content, in a day.

The nuclear moisture-density guage uses gamma ray attenuation to measure the total, or wet density. All of the comments made earlier in the Water Content Test Method subsection of this report apply equally to the measurement of density. The two tests, water content and density, can be made in five to ten minutes with a single positioning of the nuclear guage. In the preferred direct transmission mode, all of the soil between the source and the detector is tested. If the source is at the bottom of a compacted soil lift, then the guage measures average lift density at the test location. Water content, on the other hand, is usually measured in the backscatter mode. Therefore, the water content of the uppermost one to two inches of the soil mass contributes most of the measurement. If there is a moisture gradient or discontinuity in the soil mass to the depth of the probe, an error in dry density calculation will be made. For this reason, the test should always be made on a freshly cleared surface (as described in the instrument's instruction manual), before it starts to dry.

In summary, all of the test methods are capable of measuring field density with reasonable accuracy and precision. The direct methods are straightforward, use rugged and inexpensive equipment, and take considerable time to perform. The nuclear guage method uses expensive equipment (yet its purchase price is less than the labor cost of one inspector/technician for one year), requires constant attention to calibration and maintenance, and yields very rapid nondestructive test results. Operator fatigue with the nuclear guage is less than it is with the simpler methods. And with the nuclear guage the inspector is left with more time to observe construction operations and perform other tests. Rapid results are particularly valuable during process control tests of fill compaction, for they contribute significantly to lower construction costs.

Specific Gravity Test Method

The specific gravity of most soils tends to be fairly uniform in a limited area because of the sorting of many geologic processes. This is demonstrated in Table 3-1 where a coefficient of variation of one to four percent has been reported.

Because of the relative uniformity of specific gravity, most tests to define it in a soil mass are made during the site characterization. The tests must be performed in a laboratory environment and can take one or more hours to perform. Therefore, the performance of this test is suitable as an occasional check on the consistency of earlier test values. It is, however, of little concern or value for process control or acceptance testing.

Grain-Size Distribution Tests

These test methods use square screen openings to separate soils into size fractions. Soils are generally classified as: (a) gravel, larger than the No. 4 screen; (b) sand, between the No. 4 and No. 200 screens; and (c) fines, smaller than the No. 200 screen (Dept. of the Army, 1970). The distribution of particle sizes for gravel is of little concern at a disposal facility, especially during construction. Sand sizes are fractionated on square-opening screens ranging from four openings per inch (No. 4) to 200 openings per inch (No. 200). Finer sizes are fractionated on the basis of the rate of sedimentation of equivalent spherical particles in water, using Stokes' Law to calculate the rates. None of the methods are rapid tests, and all require performance in a laboratory environment and the nearly constant attention of a test technician.

Sand samples must be thoroughly dried before they can be shaken through a nest of sieves for the *sieve analysis test*. If the sand contains very few fines, the entire test for a single test portion can be made in under an hour, if hot air drying is used. The shaking through the screens, weighing of individual fractions, and calculations can be performed by one man with a mechanical shaker in under 30 minutes. Sampling time, travel time, and drying time are variables. Several samples can be prepared at the same time, with the per test time thus reduced.

If the sand contains plastic fines, drying will cause the clay particles to adhere to the fine sand sizes, giving erroneous test results. If a wet test portion is weighed (a moisture sample tested for correction of the wet sample to dry weight) then the wet sample can be *washed through the No. 200 screen*. The fine particles will pass and the coarse residue, when dried, can be used for the sieve analysis test. The loss in weight is the fines content. The fines are not normally retained. The test is time consuming and requires constant attention from the operator. It also requires a source of water and of drying heat. Two tests per hour would be a rapid test rate; however, the results would not be available until the residue is dried and sieved.

The *standard hydrometer test* requires extensive time and expertise for sample preparation and for test performance. A vibration free test area, glassware, and temperature controls are needed. The test requires several hours to perform, including the time for soaking in the deflocculating agent. This is the only *exact* method for determining the percent silt sizes (0.074 mm to 0.002 mm) and the percent clay sizes (finer than 0.002 mm). Several samples can be tested simultaneously. This test may be useful for acceptance testing but is not normally used for process control.

The *pipette method* and the *decantation method* (Mills, 1970) are variations on the standard hydrometer method. They are useful only to establish total percent silt (0.074 mm to 0.002 mm) and total percent clay (finer than 0.002 mm). Stokes' Law can be used to determine the settling rate of clay sizes. The soil samples are placed in a container of specified height and deflocculated with standard dispersing agent for a period of one hour. The soil-water mixture is agitated and then allowed to sit quietly for a specified time, usually a few minutes. This is the theoretical time for settlement of all sand and silt sizes below a specified level. At that time, all liquid with clay in suspension is removed by either a pipette or by decantation. This is repeated until the water is clear, after the settling time, indicating that all clay sizes are gone. Then the residue is dried and tested by sieving; the material passing the No. 200 screen is then all of silt size. This form of sedimentation test for silt and clay sizes should, when properly conducted, yield the same useful information as the more involved hydrometer test, but with equipment better suited to field laboratory use. Several samples can be tested at the same time; with total time per sample of about two hours. Before use, the technique and equipment should be calibrated against the standard hydrometer test to produce any systematic, or require performance in a laboratory environment and the nearly constant attention of a test technician.

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Atterberg Limits Tests

The liquid and plastic limits, and the plasticity index, are used primarily in the identification and classification of soils. They are not fundamental parameters; rather, they are used only as indicators of potential behavior. In association with clay content (finer than 0.002 mm), an activity ratio can also be calculated, which is related to mineralogy, and thus also to the potential for swell and shrinkage.

The numerical values for the Atterberg limits needed for the identification of a sample according to soil type or group need not be exact. A five or ten percent variation, or error, is often acceptable for soil classification purposes. For most common clay minerals, the liquid limit is dependent upon the types and amounts of clay minerals present. It may vary from 25 percent water content to well over 100 percent. The plastic limit varies, usually, over a very small range, about 15 to 30 percent water content; however, when particular clay minerals predominate, the plastic limit can vary over a much wider range of water contents (Spigolon, 1956).

Except when the Atterberg limits are to be used in a well researched empirical correlation with another soil parameter, a five to ten percent error yields a reasonably correct identification and consistency within a soil group. The one point liquid limit test will yield a liquid limit within one or two percent error of the standard multipoint liquid limit. Considering the time savings realized, with little or no sacrifice in the value of the test, the one point method is frequently used. In view of the limited experimental data usually associated with most correlations, it is probably acceptable even in such applications. The Atterberg limits tests require up to one hour to perform, not including the drying time needed to determine moisture content. A competent technician can perform several tests concurrently, so that ten or twenty tests per day can be performed. These are laboratory tests and are not amenable to field use. However, they can be reasonably approximated by the visual-manual field expedient methods of ASTM (1982) Designation D 2488-69, "Practice for Description of Soils (Visual-Manual Procedure)".

Cohesive Soil Consistency Tests

Table 2-2 listed a relationship between unconfined compressive strength and consistency; this is an attempt to quantify, by means of a test result, a relative term. The standard unconfined compression test, ASTM (1982) D 2166-66, "Tests for Unconfined Compressive Strength of Cohesive Soil", requires either an undisturbed or a remolded sample, trimmed to a specified size, and tested in a laboratory loading device at a constant loading rate. The preparation, testing, and calculations for a sample can take well over 30 minutes of an operator's time. This does not include sampling and delivery time. The procurement of an undisturbed sample can be time consuming.

A number of field expedient unconfined compression test devices are available. These usually include a small, simple device for securing a test specimen from the surface area of a soil deposit. Or, they include a portable, easily operated field testing machine for stressing the sample. Most of these devices are useful and will yield an unconfined compressive strength close to the laboratory derived value. Considering the broad classifications of consistency, great precision cannot be justified. As it is a process control test, rapidity and ease of testing are of utmost importance, and the field devices are thus qualified. For acceptance testing, some reasonable precision is required. Since, as Harr (Table 3) has shown, spatial variability of unconfined compressive strength is large compared to the total variability, then a very precise test is unnecessary (see Equation 3-13 and the text immediately following).

The great imprecision of the field identification methods of Table 2 have lead to the development of testing devices which provide numerical values, presumably independent of the technician's bias and capabilities. These include the Hand (Pocket) Penetrometer and the Torvane. Both are useful devices for their intended purpose of aiding in establishing a consistency classification. Their accuracy (systematic) error is questionable and their markings are sufficiently spaced that precision is good on a general basis. If the devices are viewed only as alternatives for a calibrated thumb they can be a valuable site media verification or process control device. They should not be relied upon for acceptance testing of unconfined compressive strength.

Water Content/Density/Compactive Effort Tests

Specifications for compaction control usually require that a soil be compacted to a field density of a value at least equal to a predetermined percentage of the density derived from a specified laboratory compaction test method. Often, the water content of the soil at the time of compaction is specified. This is done to achieve a soil structure (dispersed) which will provide low permeability of the compacted soil at a disposal facility. Because the test derived density is a function of the soil type in addition to the test procedure, even slight variations in the soil composition can cause variations in the density. Therefore, it is most desirable that every field density/water content test for compaction control be compared to a laboratory compaction test on the same soil. This is not always possible because of the large number of field density tests necessary to evaluate a compacted fill construction block and the relatively significant effort required for the laboratory compaction tests.

In the early 1930's typical compacted fill specifications directed the contractor to use specific equipment, specific soil from an approved borrow area, a specific lift thickness, and a specific number of uniformly placed passes of the roller (Johnson and Sallberg, 1960). It was recognized earlier that, for a constant field compactive effort, there was a relationship between field density and water content of the type shown in Figure 5, and that this was used by engineers of the time in establishing the compaction criteria.

Proctor (1933), in his classic articles, advanced two ideas: (1) he demonstrated the need for moisture control; and (2) he developed a laboratory compaction test to establish the necessary water content. The soils of the southwestern U. S. tend to be naturally dry. When these are placed in a fill at natural water content and compacted, the fill is usually very firm. Proctor showed that a soil used in an earth dam, for example, and compacted dry and hard would, upon wetting, become very soft. If it were placed initially at the optimum water content, and if the strength were satisfactory, then no further softening would occur upon wetting.

The moisture-density relationship at a specified, constant compactive effort, was usually determined at the site by using a contractor placed test section at various soil water contents. Then, the contractor would be required to use the same soil at the same compactive effort at the field determined water content. Proctor set out to develop a laboratory test that would duplicate the results of a field test section, obviating the need for the costly field work. This would also permit retesting for a change in soil composition, but always at the same field compactive effort.

The test developed by Proctor (1933) was the basis for all present day impact-compaction tests (Hveem, 1957). The original test resulted in the present 25 blow Standard Proctor Compaction Test, ASTM (1982) Designation D 698-78, "Moisture-Density Relations of Soils and Soil-Aggregate Mixtures". That test, as described above, defines the "maximum" density and "optimum" water content for a single laboratory compactive effort, and was originally intended to duplicate the typically specified field compactive effort of the early 1930's. It can be used to duplicate that effort for any cohesive or granular soil, without the need for a field test section.

As a result of the usefulness of the laboratory test and its sensitivity to soil composition change, there developed in the late 1930's, and through the war years of the early 1940's, a tendency toward the end result compaction specification commonly used today. Contractors were expected to compact the soils to a high percentage of their maximum density, at or near the optimum moisture content, as determined by the laboratory test. Compliance was determined by a field density/moisture test. This type of end result specification is extensively used today.

During the early 1940's, at a time of extensive airfield construction, higher compactive efforts than ever before were used on base courses. The standard Proctor [ASTM (1982) Designation D 698-78] test was no longer applicable. Therefore, a modified Proctor test, at a higher laboratory compactive effort was developed. This became the 25 blow Modified Proctor Compaction Test, ASTM (1982) Designation D 1557-78, "Moisture-Density Relations of Soil and Soil-Aggregate Mixtures".

In the 1950's there developed a confidence in compacted fills and these were end result specified for highways, airfields, dams, and structural fill. A wider variety of compaction equipment was developed. The prescription type of specification gradually faded, largely as the result of legal problems resulting from its use. The laboratory compaction tests became "index properties" (Peck et al. 1974) sensitive to soil composition, but no longer were they commonly used as a method to establish optimum moisture content.

With the advent of specifications for light compaction of fill at disposal facilities, using tractor treads for example, there has been an attempt to devise laboratory compactive efforts to duplicate field compaction, in the original Proctor manner. This has resulted in Nonstandardized Proctor Compaction Tests in which the number of blows per layer, or even the number of layers, is different from the ASTM standard methods.

Johnson and Sallberg (1962) discussed the various compaction tests that are in use. Because there sometimes existed a discrepancy between the laboratory impact-compaction/water content/density curves and the field derived curves, other forms of compaction, such as kneading, have been used in the laboratory (Antrim, et al. 1970).

All of the impact and kneading compaction tests have limitations and require a laboratory environment. For low plasticity soils, a complete test can be performed in one to two hours if a mechanized blender is available. Operator fatigue can be lessened by the use of a mechanical compactor. Drying of samples for water content determination can take from a few minutes to overnight, as discussed earlier in this report. If the soil is a medium to high plasticity clay, then time delays may be needed to alter the water content of the soil throughout the small lumps of soil prepared for testing. This time will be a function of the permeability of the soil and its percent fines.

A very useful, but uncommonly used, apparatus and test method is the Harvard Miniature Compaction Apparatus (Wilson, 1970). This is a kneading type compactor using a small mold, about 1.31 inches diameter by about 2.82 inches high, suitable only for fine grained soils (soils for which half the material will pass a No. 200 screen). Because of this smaller apparatus and the simplicity of its use, the method can be easily adapted to field laboratory operation, or even to field use at the compaction site. The number of layers and number of tamps per layer can be varied as necessary, as with the Proctor tests. Therefore, the Harvard Apparatus can be used to establish a moisture-density curve comparable to that established by the larger equipment. For both types of apparatus, the relationship between the field and the laboratory compactive effort must be established for the test to yield the optimum moisture content. It is likely that the moisture-density curve from the Harvard Apparatus kneading action will come closer to the field curve than the moisture-density curve from the impact compaction test, because its kneading action is closer to those actions actually accomplished by sheepsfoot and rubber tired rollers. Furthermore, the apparatus yields a cylindrical specimen, when extruded from the compaction mold, that is of the correct dimensions for unconfined compressive strength testing. In summary, it is the authors' opinion that the Harvard Apparatus test lacks only the mantle of standardization to equal or exceed the usefulness of the more conventional Proctor impact tests for fine grained soils.

The time consuming and tedious laboratory compaction test procedures do not lend themselves to rapid or frequent testing. Theoretically, every field density test should have an accompanying laboratory derived curve if the specifications continue to be written on the basis of density. This has lead to the development of several quick methods, all based on the nest of curves concept.

The files of many agencies, such as state Highway Departments, contain thousands of curves of standard or modified Proctor compaction tests for a variety of soils. Woods and Litehiser (1938) developed a family of curves for Ohio soils, all of about the same shape, and varying in maximum density and optimum moisture content. Similar nests of curves have been developed by others, either on a regional basis or on a job site basis. The Ohio Highway Department Method uses the result of a compaction test of the field density soil, wetted to near optimum moisture content, and a nest of curves of Proctor Needle Penetration resistance [Proctor, 1933; ASTM (1982) Designation 1558-71, "Test for Moisture-Penetration Resistance Relations of Fine-Grained Soils"], to establish the "correct" moisture-density curve, from which the maximum density and optimum moisture are read.

Variations on the nest of curves method involve the (a) One point Compaction Method, and (b) the Two point Compaction Method. These are described in detail in Appendix B of Engineer Manual EM 1110-2-1911 (Dept. of the Army, 1977). In the one point method, the soil from the field density test is allowed to dry to a water content below optimum. It is then compacted using the laboratory procedure at the one water content. The water content and density establish a single point in the nest of curves, from which the estimated correct curve is developed by drawing it to the same shape as the rest of the family, through the test point. The two point method is similar except that two points are established. This is expected to give a better estimated curve.

The nest of curves methods are only as good as the basic data. Where the local soils have been well tested and the data are consistent, these methods can give fairly reasonable estimates of the true moisture-density curve. This is better than the common method of running one test curve for a soil type and applying it to all soils on the site that can be matched to it visually, for visual matches are often misleading.

Another rapid compaction test method is that of Hilf (1970), who developed it for use on Bureau of Reclamation projects. In this method, the field moisture is estimated to be on the dry side of optimum. A field sample is selected and compacted at field moisture. Second and third samples are compacted at two percent and four percent above the field moisture in order to bracket the unknown optimum moisture content. A curve is fitted to these points and, without the need to determine water content, the percentage of maximum density and the difference of the fill soil from optimum moisture is established. This method is useful only for low plasticity cohesive soils, liquid limit less than 50, so that the moisture additions will mix well with the soil. The total test time is about one hour. This is a potentially useful method, especially when compared with the more labor intensive, conventional five point laboratory impact tests (Winterkorn and Fang, 1975).

Cohesionless Soil Relative Density Tests

Moist sands bulk, or become less dense, when poured or dumped, because of a film of moisture about each grain and the effect of surface tension. Therefore, in the performance of maximum and minimum density tests, the sand samples must first be thoroughly dried. This is cumbersome and time consuming because of the quantities involved. The maximum density test requires a vibrating table; this is not normally found at a field laboratory. However, sand samples can be obtained from the source stockpiles and tested ahead of time. Or, samples can easily be taken at the end of the day from the fill and tested overnight, with results available within one hour or less after the sand is dried.

The Modified Providence Vibrated Density Test is a field expedient test for maximum density. It uses the blows of a hammer on the mold to cause densification, rather than the more consistent densification caused by a vibrating table. If performed properly, this procedure should be almost as valid as the method requiring the use of a more expensive vibrating table. Also, this method can save the time and effort of transporting samples to the central laboratory.

It has been the experience of one of the authors (Spigolon) that process control of sand densification can be made by the use of a penetrometer. On a major fill project in Memphis, Tennessee, a dredged sand, with about 15 percent content passing the No. 200 screen, was being vibration compacted to 75 percent relative density. A 5/8 inch pointed end steel rod was driven into the fill by use of a 20 lb hand-held drop hammer. This device was used to prepare a hole in the soil for insertion of the radioactive source rod of a nuclear moisture-density gage. The test technicians quickly became adept at using dynamic penetration resistance (number of blows) of the hammer device to tell if the fill sand had been adequately compacted before the density test was made.

Soil Color Tests

Although not a formal index property, the color of a soil can often be used to compare soils. Often, differences in mineral composition or even oxidation (reduction) above or below the water table can be compared by the color. For greatest consistency among technicians, it is recommended that standard Munsell color charts be provided for field use during the site investigation and also during site media verification.

Organic Content Tests

The organic content of some soils is so great that they are unusable for fill as a liner or as a cover. As a specification item, the organic content can only be tested by elaborate chemical laboratory tests. Among procedures for determining organic content are those of Schmidt (1970) and Rankin (1970).

Permeability Tests

Specifications for compacted clay liners for disposal facilities often require that samples be taken from the fill and laboratory tested for permeability. A complete discussion of this topic is beyond the scope of this report. The reader is referred to the papers by Olsen and Daniel (1981) and an EPA report-in-progress by ABC Dirt, Inc. (1981). There is some concern that the action of securing the samples densifies them and produces permeabilities as much as one or two orders of magnitude in error. The variation of permeability over a site was discussed in the paper by Vieira, Nielsen, and Biggar (1981) (see Section 6, Recommendations for Further Study).

Geomembrane Hydrostatic Leak Detection Test

There is one commonly used method for checking the impermeability/integrity of an entire installed geomembrane which is very unlike the geomembrane/geotextile tests and observations to be discussed. As will become evident, this hydrostatic leak detection test does not involve a very formalized or specific method. Thus it does not meet the definition of a test. However, the method is also more than a mere observation. This is why the hydrostatic leak detection test is presented here.

The hydrostatic leak detection test calls for the filling of an entire geomembrane-lined excavation with water, so as to completely submerge the geomembrane (or at least that major portion of it which will be lining the waste), and, in effect, create a pond. Any leak in the geomembrane is then detected by the presence of air bubbles. Pinhole size leaks can be detected by causing air pressure beneath the geomembrane to encourage air bubbles. This air pressure can be the result of so simple a procedure as having a man walk over the geomembrane, particularly along the seams (likely locations for leaks).

There are limitations to the hydrostatic leak detection test. The detection of a leak also means the seepage of water into the soil beneath the geomembrane. Also the pumping costs, both in and out of the excavation, are considerable in terms of the time, equipment and labor required.

However, the hydrostatic leak detection test can provide great assurance in the impermeability/integrity of an installed geomembrane. It would be a particularly desirable method for an inspection group which wanted great assurance that an installed geomembrane for a surface impoundment had no detectable leaks.

Geomembrane and Geotextile Seam Integrity Tests

Geomembranes and geotextiles receive expanded discussion in this report. This subsection on geomembrane and geotextile seam integrity tests includes discussions of general considerations, field test methods, observations and off-site materials inspection.

A discussion of quality assurance field test methods and observations for geomembranes and geotextiles used in a hazardous waste disposal facility must begin with an explanation.

The techniques for the installation and use of these products (geomembranes and geotextiles) are still evolving. The development of a field test method or observation to assure that a technique will work to its designed-for performance standard occurs after the technique has been proven. And the field test method or observation is developed to assure the performance of that specific technique. That the techniques are still evolving obviously means that so are the quality assurance field test methods and observations (Reference: verbal communication with Paul Miller, Vice Chairman, ASTM Subcommittee D 18.19, "Geotextile Applications" and ASTM Subcommittee D 13.61, "Geotextiles"). Thus any presentation of accepted and commonly used field test methods and observations in this subsection must be in the context of this evolutionary reality (see Section 6, Recommendations for Further Study).

The use of a geomembrane or geotextile in a hazardous waste disposal facility requires that quality assurance be provided for both the workmanship and the material. The quality assurance for the workmanship can be divided into two aspects: (1) quality assurance of the workmanship involved in the seam bonding, and (2) quality assurance of the workmanship involved in the installation of the product. The quality assurance of the workmanship involved in the seam bonding will be discussed in the subsection on Field Test Methods. The quality assurance of the workmanship involved in the installation of the product will be discussed in the subsection on Observations. The quality assurance of the material will be discussed later in the subsection on Off-Site Materials Inspection.

Field test methods: The quality of the workmanship involved in seam bonding can be assured by testing the seam's integrity after bonding. Methods for testing the seam's strength include the bonded seam strength, breaking strength and peel adhesion methods. Each of these methods provides credible assurance of the seam's strength, but as they differ in the results they provide no relative meriting of these methods will be attempted. Methods for testing the seam for anomalies include the air lance, vacuum seam and conductivity methods. The air lance is the most rapid of these methods but also the least capable of locating all anomalies. By itself it does not adequately assure seam integrity. The vacuum box and conductivity methods both provide great degrees of confidence in the seam integrity. Each has its relative merits and the preference of one over the other should be left to the permittee's forces as a site-specific, usage-specific decision.

All three of the seam strength testing methods require the cutting of bonded seam specimens. This is a destructive requirement causing the effort involved in specimen replacement. An alternative is to bond a seam of greater length than that required. Then the specimens can be secured from the excess seam and these methods would then not be destructive in nature. However, this alternative obviously also contravenes the random sampling concepts described in Section 3. The decision to select this alternative is therefore left to the permittee's forces, to be made on a site specific basis.

As is obvious, these methods test only the seam integrity. This limitation is also addressed in Section 6, Recommendations for Further Study.

Observations: As has been stated before, the worth of the observations in a quality assurance program for a hazardous waste disposal facility depends more on the technical expertise and willingness of the quality inspector than on specific details of observation technique. This is certainly true for observations on the workmanship involved in the installation of a geomembrane or geotextile.

The quality inspector should assure that the workmen are in fact installing the product as per the design by some acceptable, and nondestructive (to the product) technique.

The quality inspector should also conduct a one hundred percent inspection of the product after installation. During this inspection he should look for anomalies. If the product installed is a geomembrane, anomalies he should look for include pinholes, air bubbles beneath the membrane, inadequate cover over the membrane particularly along the shoulders of a trench such that the membrane would be exposed to direct sunlight, etc.

The most important consideration for a quality assurance program which includes observations to assure the quality of workmanship involved in the installation of a geomembrane or geotextile is the selection of the quality inspector to make these observations. The inspector selected should be competent, willing and expert in geomembrane and geotextile installation. This selection is critical to the effectiveness of the entire program.

Off-site materials inspection: When a geomembrane or geotextile is included in the design of a hazardous waste disposal facility, the permittee and his design group expect the product to perform to the specifications provided by the manufacturer. But there is an inevitable degree of uncertainty as to whether the product which actually arrives on site will in fact perform to those specifications. This uncertainty results in part from doubt that the product is, in fact, what it is supposed to be. This uncertainty will exist in some small degree regardless of the credibility of the manufacturer. The permittee and his design group simply have no long term guarantee that the product will perform to the specifications provided by the manufacturer.

Given the importance of protecting the human health and environment, and given the considerable costs of remedial action, the permittee and his quality assurance group will seek to dispel this uncertainty. The usual means of doing so is to order the products to be brought on site in advance and then rely on independent laboratory verification for their quality. This independent laboratory verification is not geotechnical in nature, nor is it within the scope of this report. Therefore it will only be stated that this independent laboratory verification should be of such a nature that the permittee can be given that commensurate measure of assurance (see Section 5, The Nature of a Quality Assurance Program) that the product will perform to the specifications provided by the manufacturer.

SECTION 5

THE QUALITY ASSURANCE PROGRAM

The term "quality assurance", as discussed in Section 1 of this report, includes all of those planned and systematic actions of the permittee necessary to provide adequate confidence to the regulatory agency that the disposal facility will perform satisfactorily in service. That is, it will perform in accordance with the design, and the permit, requirements. A quality assurance program, whether formal or informal, should be an integral part of the permit requirements.

A large body of technical literature has been published on the subject of Quality Assurance/Quality Control (QA/QC) programs. Nearly all of it involves manufacturing processes, nuclear power plants, or highway construction. Formal QA/QC programs in manufacturing processes (Juran, 1962; Grant and Leavenworth, 1972) and, later, in highway construction (Willenbrock, 1976; TRB, 1979) emphasize statistical quality control. Both industries involve continuous, repetitive production of a single item or a single process. A formal QA/QC organization, the use of control charts for process control, and formal acceptance sampling plans are used. The construction of nuclear power plants has followed the manufacturing industry lead in establishing formal QA/QC plans (Bohannon, 1978).

ELEMENTS OF THE QUALITY ASSURANCE PROGRAM

A quality assurance program for a hazardous waste disposal facility must account for all the considerations given. It must include (a) a well-defined plan of action, and (b) a specific plan of documentation, including directives for disposition of records. Regardless of the existence of any watchdog organization, all of the QA programs should be planned and executed as if a watchdog organization existed.

The Quality Assurance Plan of Action

The permittee should prepare a written plan of action for the implementation of construction quality assurance. Despite the relative small size of some disposal facilities, the human health and environmental protection features of such projects require greater than ordinary attention to assure the regulatory agency (through its watchdog organization, if it exists) of their quality.

The suggested plan given below is based upon the proven and effective "Contractor Quality Control Plan" of ER 1180-1-6 (Dept. of the Army, 1978). The permittee's quality assurance plan should include:

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a. The QA organization planned

b. Proposed methods of performing QA inspections, both for process control and for acceptance sampling and testing; this will include inspections of the subcontractors' work

c. Proposed methods for initiating the corrective action when the QA inspection determines that a block of work is unacceptable

d. Area of responsibility and authority for each individual to be used in the inspection group for QA

e. Name and qualifications of each individual assigned a QA inspection function; method of establishing and verifying inspector qualifications to perform specific tests or tasks

f. How inspection will be performed:

    (1) By inspectors employed by the permittee with designation of individuals with their qualifications and specific tests to be performed

    (2) By subcontract inspectors, approved by the regulatory agency

    (3) Use of test methods, approved by the regulatory agency

    (4) Location, availability, applicability, and calibration of test facilities and equipment

g. Procedures for advance notice and coordination of special inspections where required

h. Procedures for reviewing all shop drawings, samples, certificates or other documents for compliance with permit requirements and for certification of their acceptability to the regulatory agency

i. Reporting procedures, providing for submittal and/or storage, at specified intervals, and with proposed report format (see Quality Assurance Documentation, later in this section)

j. A copy of a letter of direction to the permittee's inspection representative, responsible for quality assurance, setting forth his duties and responsibilities, and signed by a responsible official of the permittee if not by the permittee himself

The regulatory agency, in reviewing the permittee's quality assurance plan of action, should give particular attention to a plan for education of workmen, construction management, and inspectors on the various quality requirements of the disposal facility and the reasons for their existence.

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Quality Assurance Documentation

The ultimate objective of the project documentation is to provide a permanent record of the permittee's self evaluation of his construction to assure the regulatory agency that it was done in accordance with specification, and permit, requirements. Because of the human health and environment protection needs and because of the need for providing confidence to the regulatory agency, the documentation must be complete.

Unless there is a specific permit directive for the amount and type of documentation, there will be the human tendency to reduce it to a minimum. This will be especially true if there is no action taken with the documents, i.e., review, audit, or submittal to a watchdog organization. The attitude may well be, "If nobody is going to look at it and check it, why do a lot of it?" Therefore, it is recommended that the following records be maintained:

a. Daily inspection reports; daily project diary kept by the senior inspector at the facility

b. Data sheets; test and/or observations

c. Block evaluation reports

d. Design acceptance reports

e. Summary and checklist

Daily Inspection Reports

A daily summary report, a project diary, should be kept by the senior inspector. This report provides the chronologic framework for identifying and recording all other reports. At a minimum it should include the following:

a. Date, project name, location, and other identification

b. Data on weather conditions

c. Unit processes, and locations, of construction underway during the time frame of the report

d. Equipment and personnel being worked in each unit process, including subcontractors

e. Descriptions of areas or units of work (blocks) being tested and/or observed and documented

f. Off-site materials received, including quality verification documentation

g. Calibrations, or recalibration, of test equipment, including actions taken as result of recalibration

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h. Decisions made regarding acceptance of units of work (blocks), and/or remedial action to be taken in instances of substandard quality

i. Signature by the permittee's senior person responsible for the inspection program

Field/Laboratory Data Sheets

Original, handwritten data sheets should be maintained as part of the project records. The requirements, and some example formats for data sheets, for many of the necessary tests are given in Appendix B with each test description. Because of their non-specific nature, no format can be given for sheets to record observations. Recorded observations may take the form of notes, charts, sketches, photographs, or any combination of these. For identification, all data sheets should contain, as a minimum, the description or title of the test or observation, the location of the test/observation, type of test/observation, procedure used, personnel involved, results of the test/observation, and comparison with specification requirements. Finally, each data sheet should be signed by the senior member of the test/observation group involved.

Block Evaluation Reports

The design specifications delineate the quality characteristics which must be inspected for each construction process. In each of these processes the work is divided into blocks sized to accommodate the inspection program. Therefore within each block there can be several quality characteristics tested, each by different tests, each recorded on different data sheets. These data sheets must be organized at the block level into a block evaluation report. Each block must have its own separate block evaluation report. In this way when the project or some well defined portion of the project ends, the entire construction work can be summarized by a summary of all the block evaluation reports. Also, given that the documentation is correct, the quality of the entire project can be checked by comparing the design to a summary of all the block evaluation reports.

Block evaluation reports should, at a minimum, include the following:

a. Description of block; use project coordinate system for areas and appropriate identifiers for other units of materials or work

b. Quality characteristic being evaluated; reference to section of specifications

c. Sampling method; how it was established

d. Sample increment locations; describe by coordinates or by a location sketch on the reverse of the sheet

e. Tests or observations made; define procedure by name or other identifier; attach data sheets; give number of sheets and identify

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f. Summary of test data; tabulate data and give block average and block standard deviation

g. Define acceptance criteria; compare sample data with requirements; indicate compliance or non-compliance; in the event of non-compliance indicate that the block was determined to be unacceptable and that corrective action was initiated; in the event of non-compliance and block non-acceptance, document the corrective action as per a. through g.

h. Signature of senior member of inspection group involved

Design Acceptance Reports

All daily inspection reports, block evaluation reports, and field/laboratory data sheets should be submitted to the permittee's design group for evaluation and analysis for internal consistency and consistency with similar previous work, i.e. acceptance. One of the objectives, and benefits, of prompt evaluations is that errors, inconsistencies, anomalies, and other problems can be detected and corrected as they occur, i.e. when corrective action is easiest.

A periodic Design Acceptance Report should be prepared for project records and for possible submission to a watchdog organization. The report should accept the work and indicate that it complies with specification and permit requirements. Each report may cover a time period, or a phase of work, or a subsection of the total project, or the entirety of a unit process. This report is also the periodic certification by the permittee of his compliance with permit requirements.

Summary and Checklist

It may be desirable, at the closure of any portion of a disposal facility, or at the closure of the entire facility, to prepare a final summary report. If the periodic block evaluation and design acceptance reports are complete and voluminous, a final index or menu report will be helpful in showing the content of all records and where they are located. This summary may be coupled with any final certification required of the permittee. This summary and checklist will be most important for the sake of quality assurance documentation access and review.

Disposition of Records

Except for the handwritten field/laboratory data sheets, all other reports are compatible to reporting and/or storage in either (a) photographic, or (b) computer-compatible methods. It is expected that the original of all reports, especially those containing signatures, will reside with the permittee in a publicly acknowledged repository.

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The use of microfilm or microfiche provides a means of reporting that requires very little storage space at the reported-to organization. This method also allows recording of handwritten originals and of the inspectors' signatures. By this method, information retrieval is accomplished by visual-manual searches using a suitable microfilm reader machine.

Digital computer technology, including microcomputers, has progressed such that even small engineering and business firms are using data base management and data storage systems. Minimal paper and storage costs, coupled with the speed and flexibility of data recovery and data transmission, undoubtedly make computer-compatible methods desirable to use for hazardous waste disposal facility documentation.

Although photographic and computer-compatible methods are presently available, and may be efficient and cost effective, the relatively small size of most disposal facilities means that conventional, paper-based, methods will likely remain in use for the time being. Thus the use of photocopy machines to make copies of reports for submittal to a review or watchdog organization must be considered acceptable in spite of the significant filing space requirements.

As a final documentation event, the permittee should require his design group to update the facility design drawings at the closure of the facility. These drawings should be equivalent to as built drawings, and with the inspection summaries, will provide data in the event remedial action is required in the future or in the event litigation, concerning the construction and operation of the hazardous waste disposal facility, arises.

SUMMARY OF THE QUALITY ASSURANCE PROGRAM

The following flowchart, Figure 13, depicts the elements of the quality assurance program which have been described in this section.

The EPA (Block 1), public (Block 2), and permittee (Block 3) arrive at a level of quality (Block 4) for a given proposed hazardous waste disposal facility. The permittee performs a site characterization (Block 5) for the proposed facility. The level of quality arrived at and the site characterization are used by the permittee to submit his permit (Block 6). The permit includes, amongst other information, design guidance and specifications (Block 7) as well as the permittee's quality assurance plan of action (Block 8).

The design guidance and specifications are used by those performing the permittee's design function (Block 9) to produce the design (Block 10). (It should be noted that this program is for the quality assurance of construction and not the quality assurance of design.) The design is furnished to those responsible for the permittee's construction and operations function (Block 11). They use the design for all phases of their work: initial construction, operation and closure. Their work is performed in blocks to accommodate the quality assurance plan of action.

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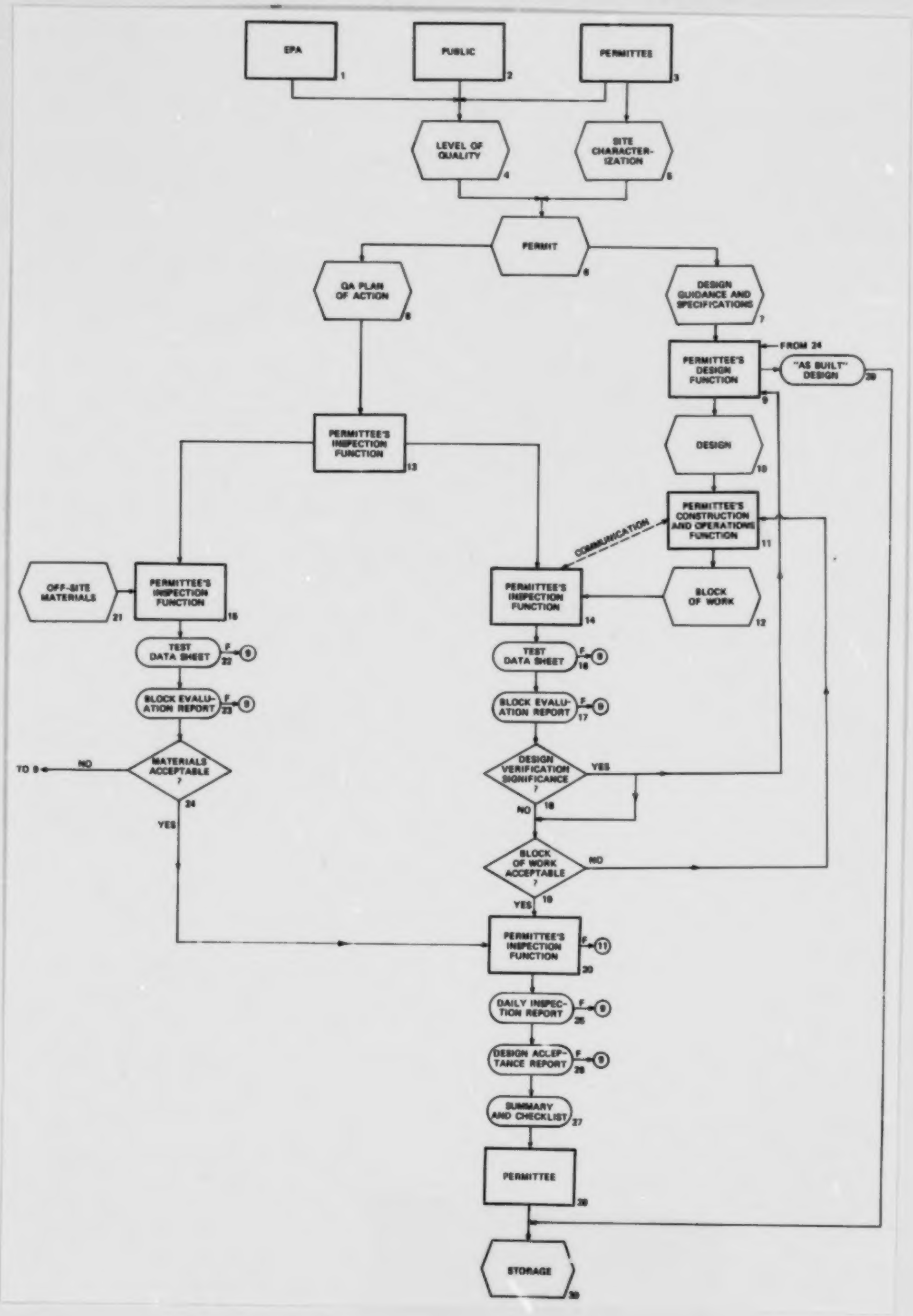

Figure 13. The Quality Assurance Program.

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Each block of work (Block 12) is observed and/or tested by those responsible for the permittee's inspection function (Blocks 13, 14). These inspectors are in constant communication with the construction personnel. The two groups strive to catch and correct mistakes as these happen. The two groups work synergistically to achieve the desired and specified level of quality. The inspectors continually observe all construction and perform tests and/or observations on finished blocks of work. In this way the inspectors provide both process control and acceptance testing of the construction.

Every observation and/or test is documented by a test data sheet (Block 16). A copy of each test data sheet is furnished to the designers (Feedback Block 9). Every block of work's inspection and acceptance or non-acceptance is documented by a block evaluation report (Block 17). A copy of each block evaluation report is also furnished to the designers (Feedback Block 9).

The inspectors determine if, during the construction of the block, any information of design verification significance was learned (Block 18), e.g. the exposure of site media contrary to that expected based on the site characterization. If there is information of design verification significance learned, they forward this information to the designers.

The inspectors also determine if the block of work is acceptable based on the level of quality specified by the design (Block 19). If the block of work is unacceptable the construction personnel will have to perform the same work over, thus renewing the construction-inspection cycle. If the block of work is acceptable the inspectors inform the construction personnel so that they may continue their work (Feedback Block 11).

Off-site materials (Block 21) are also tested by the inspectors (Blocks 13, 15). The inspectors prepare documentation for each test (Block 22) and each block of off-site materials (Block 23). Copies of both the test data sheets and block evaluation reports thus prepared by the inspectors are furnished to the designers (Feedback Block 9).

The inspectors determine if the off-site materials meet the level of quality specified by the design (Block 24). If the materials are unacceptable, the designers are so informed. The designers must then attempt to procure off-site materials which do meet the level of quality specified by the design, or they must make modifications to the design based on the quality of the off-site materials on hand.

The inspection supervisor prepares a daily inspection report at the conclusion of the day's work (Block 25). A copy of this report is furnished to the designers (Feedback Block 9).

The inspectors also prepare periodic design acceptance reports (Block 26). These are furnished to the designers for their use in improving or verifying the design.

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The inspectors complete their quality assurance documentation by the preparation of a summary and checklist (Block 27) to index all of their documentation. This summary and checklist is verified and signed by the permittee (Block 28), who is ultimately responsible for the quality of the facility.

The designers use the design acceptance reports and the other feedback from the inspectors to prepare a final as built design (Block 29) of the facility.

This as built design, along with all the other quality assurance documentation (test data sheets, block evaluation reports, daily inspection reports, design acceptance reports and the summary and checklist), is maintained for ease of access and review in suitable storage (Block 30).

Thus the program for the geotechnical quality assurance of the construction of a hazardous waste disposal facility is a closed loop, redundant system. It is also a completely documented system which lends itself well to the protection of human health and the environment.

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SECTION 6

SUMMARY

This section of the report summarizes the previous five sections and presents recommendations for further study or investigation.

SUMMARY OF THE REPORT

The permittee of a hazardous waste disposal facility maintains a relationship with the regulatory agency that is unique in the construction industry. During construction, operation, and closure, the permittee is responsible for: design verification, construction and operations, and quality assurance inspection. The regulatory agency derives confidence in the project quality from the permittee's documentation of his work.

This report presents four major topics related to the permittee's responsibilities during construction, operation, and closure of a hazardous waste disposal facility:

a. The geotechnical parameters that should be tested and/or observed and documented are identified and described.

b. The selection of sampling plans and sample sizes for the geotechnical parameters are discussed within a statistical framework.

c. The commonly used laboratory and field testing and/or observation techniques needed for the investigation of the geotechnical parameters are identified and described.

d. A quality assurance program suited to the unique responsibilities of the permittee is presented and discussed.

The functions of the quality assurance inspection program during construction operations are (a) to evaluate the newly exposed site media, (b) to evaluate the materials and workmanship of the construction group, and (c) to assist the construction group in its process control.

The geotechnical parameters that should be tested during construction of a disposal site include the soil index properties. These are the water content, unit weight, specific gravity, grain-size distribution, Atterberg limits, consistency, and laboratory compaction tests. Given these values, several other index properties may be calculated; these include void ratio, porosity, degree of saturation, plasticity index, and classification by an acceptable soil classification system. The soil index properties are good indicators of the soil engineering properties used in design. Observations are made and recorded on those aspects of construction not amenable to formal testing.

The selection of sample locations should be made on a random basis: either a true random sample per construction block, or a systematic sample with a random start. Sample size is independent of block size; it is a function only of confidence level, maximum expected error, and block standard deviation. The statistical methods presented are recommended because they avoid the risks of relying on human judgement with its potential for bias or error. Conclusions derived by statistical methods are conducive to review.

All of the soil index properties identified are evaluated using standard test methods. Most of these standard test methods are not commonly used because of time or equipment requirements. Acceptable alternative methods are commonly used. This report contains a discussion of the merits and limitations of the various test methods. Although certain test methods may have time or cost advantages over others, no commonly used test method can be considered totally superior to the others for the same index property. Hence none are excluded from consideration for use.

In establishing a quality assurance (QA) program, the permittee should consider the effect of several factors that arise because of his unique construction related responsibilities. These include the workman, management, and inspector identification with quality; the quality assurance system; the nature and cost of a quality assurance program; the human factor; and the problem of scale. The rationale for a watchdog organization is presented.

The recommended quality assurance program includes a detailed plan of action and a documentation program. The project records should include daily inspection reports, test/observation data sheets, block evaluation reports, design acceptance reports, and a project summary. The documentation is intended to provide the necessary confidence to the regulatory agency in the quality of the facility.

RECOMMENDATIONS FOR FURTHER STUDY

This report has resulted from a study of the technical literature, visits to hazardous waste disposal facilities, the personal geotechnical experiences of the authors and their colleagues, and the extensive, collective, construction experiences of the U. S. Army Corps of Engineers. As a result of this study, several gaps in knowledge have been identified. The following recommendations are considered most useful for further study to support work related to hazardous waste disposal facilities.

Quality Assurance Specifications

The use of statistically derived acceptance sampling and testing, as discussed in Section 3, requires that the project specifications (a) use performance oriented acceptance criteria, and (b) establish quality requirements in terms of both mean and variability (standard deviation) (Willenbrock, 1976).

All naturally occurring soil deposits (the site media) and all construction processes have material variability. This natural variability must be known to the designer so that it may be incorporated in the specified quality acceptance requirements. Some of the published sources of such data were presented in Section 3.

It is recommended that an extensive literature review be made to record and summarize as many sources of measured natural variability as possible. This is a continuation of the "sigma bank" concept of the Federal Highway Administration. This work, naturally, should concentrate only on those materials and processes used in the construction of a disposal facility.

Permeability of Compacted Soil Layers

The authors are unaware of any published studies of the natural variability of the permeability of layers of compacted soil. Yet, this variability must be considered in establishing quality level requirements in the design for compacted clay liners as discussed above.

After a diligent search of literature and unpublished data in various public agency files, one or more field test sections of compacted soil should be tested for permeability in a statistically developed experimental design. Its purpose should be to establish the expected natural variability.

Rapid Compaction Control Test

Hazardous waste disposal facilities share a problem with all other compacted earthfill projects. Because the maximum density and optimum mositure content are sensitive to variations in soil composition, every field density should be compared with a laboratory compaction test curve developed from the same soil. However, the time and effort involved are usually prohibitive. The permeability of a compacted clay liner depends heavily on the soil being placed at or above optimum moisture content, making the determination of that value more important than it is in conventional earthfill work. Thus the need exists for more study of a rapid method for field control of compaction. A combination of the Hilf rapid method and the Harvard Miniature Apparatus may allow such rapid testing in the field, especially if some rapid moisture method (e.g. the Speedy device) is used.

Geomembranes and Geotextiles

Designs for hazardous waste disposal facilities can call for the use of geomembranes and geotextiles to achieve waste containment, slope stability, trench cap integrity, etc. But the permittee needs assurance that the geomembranes and geotextiles used will perform to their designed-for standard.

As discussed in Section 4, the permittee's quality assurance for these products usually results from independent laboratory verification of the products (off-site materials inspection) and observations and tests of product installation and seam bonding (workmanship inspection). The accepted test methods for the products (those that lend themselves to a quality assurance program for the construction of a hazardous waste disposal facility, as addressed in Section 4 and described in Appendix B) only test the membrane's or textiles's seam integrity. With the exception of a hydrostatic leak detection test, there exist no accepted and commonly used tests for the entire installed product's integrity which also lend themselves to a quality assurance program for the construction of a hazardous waste disposal facility. This is especially significant given the unsubstantial performance history of these products.

Additional field data and analysis are needed on the performance of geomembranes and geotextiles used in hazardous waste disposal facilities and similar projects. Additional investigation of field test methods of these products for quality assurance is also needed.

Verification of Off-Site Materials: Geomembranes and Geotextiles

As discussed in Section 4, the permittee usually relies on independent laboratory verification for the quality of geomembranes and geotextiles brought on site. The cost of such a quality assurance measure can be prohibitive, both in terms of time and money. But given the uncertainty that exists, and given the importance of protecting the human health and environment, the permittee has little alternative.

There does exist a possible answer to this dilemma. The idea of a seal of approval, an independent and credible verification of the membrane's or textile's quality, is attractive and has precedent. Such a seal would assure the permittee of the quality of the product and thus eliminate the prohibitive cost of independent laboratory verification. This idea should be given further consideration.

Geochemistry

As discussed in Section 1, geochemical considerations are beyond the scope of this report. However, this is an area where further study is recommended. This further study should, among other objectives, answer the following questions: What effects will the chemicals in hazardous waste disposal facilities have on the liners (both soil liners and synthetic liners)? What quality assurance procedures are necessary and sufficient to address the geochemistry of a hazardous waste disposal facility?

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APPENDIX A

GLOSSARY OF TERMS

acceptance sampling and testing: The sampling and testing/observation of a block of material or workmanship for comparison with specified requirements, resulting in acceptance or rejection of the block.

acceptance sampling plan: The specified procedure for performing an acceptance sampling and testing for a given quality characteristic, including block size, number and location of samples, and acceptance criteria.

accuracy: The closeness of agreement of individual measurements or the average of a large number of measurements with a "true" or accepted reference value.

assignable cause: A factor, usually due to material or process change, which contributes to variation in a systematic, or constant, manner and which can be identified.

average: The arithmetic mean value; the summation of the individual values divided by the number of individual values.

batch: A discrete unit or subdivision of a block of material within which all variation is assumed to be random, such as a stockpile of sand, a shipment of geomembrane, or a truckload of portland cement. See also Sample Unit.

bias error: A constant error, in one direction, which causes the average of a number of measurements to be offset from the true or accepted reference value. See also Accuracy, Systematic Error.

block: An isolated quantity of material from a single source. A discrete quantity of material that is presented for inspection and acceptance. A measured amount of construction assumed to be produced by the same process.

block-by-block sampling and inspection: The sampling and testing/observation of successive construction blocks for process control or acceptance evaluation.

characteristic: A measurable property of a material, product, or type of construction. See also Quality Characteristic.

coefficient of variation: A measure of variability; the standard deviation of a set of values expressed as a percent of the average, or mean, of the values.

confidence interval: The range of values that has a designated degree of assurance, or confidence level, of including the true value upon repeated sampling. See also Maximum Error.

confidence level: The probability that a confidence interval includes the true value.

confidence limits: The maximum and minimum values which define the confidence interval.

construction: The end result of processing and placing materials or products in accordance with explicitly stated conditions.

construction block: A measured amount of construction assumed to be produced by the same process. See also Block.

control of quality: Measurements of construction quality characteristics which are significant for controlling the construction materials and/or workmanship to meet specification requirements, combined with a system for initiating corrective action when off-standard quality is encountered. See also Process Control, Quality Control.

defect: A failure to comply with specified quality requirements for visual, dimensional, or physical characteristics.

duplicate samples: Two samples collected from the same block, or population.

error: The numerical difference between the measured value of a quality characteristic and its mean, true, or reference value.

fat clays: These are high plasticity clays, i.e. those having a liquid limit greater than 50. These clays are classified as CH in the Unified Soil Classification System.

geomembrane: A thin, flexible, impervious layer or sheet of plastic or rubber that is commonly used in geotechnical engineering. Geomembranes are used to prevent the migration of groundwater. They are also in strengthening applications similar to those for which geotextiles are used. Among the most widely used geomembranes are the high density polyethylenes (HDPEs).

geotechnical engineering: That part of science (and art) in which one applies the laws of mechanics and hydraulics to solve engineering problems associated with soils.

geotechnical parameters: These are quantities, derived from tests and/or observations, which are conveniently used for indirectly measuring an engineering property of soil or rock. See also Soil Index Properties Tests.

geotextile: A synthetic material in the form of cloth or mesh that is commonly used in geotechnical engineering. Geotextiles are used in the construction of pavements, earthworks and French drains. Geotextiles are also used to strengthen railroad beds and to control erosion. Among the most widely used geotextiles are the polyester fabrics.

homogeneous: Of the same nature or kind throughout; the state of being perfectly blended; zero degree of segregation.

imprecision: The degree of lack of precision; usually characterized by the standard deviation, or the coefficient of variation, of the errors of measurement. See also Precision, Standard Deviation.

increment: The portion of material removed from a sample unit (part of a block) during sampling. See also Sample Increment.

inspection: The process of measuring, examining, testing, gauging, or otherwise comparing a block of construction with the applicable requirements.

lean clays: These are low plasticity clays, i.e. those having a liquid limit less than 50. These clays are classified CL in the Unified Soil Classification System.

material: A part, component, or ingredient which, when combined with other materials, forms a product.

material quality: The quality of a material or product which is the combined effect of composition and placement process.

maximum error: The greatest difference between the estimate made from a sample and the true or reference value that may occur with a designated degree of assurance (confidence level). See also Confidence Interval.

mean: The arithmetic average; the sum of a number of individual values divided by the total number of values.

natural process tolerance: The actual capability limits of a construction process applied to a specific material; the limits within which all but a specified fraction of all measured values of a material quality characteristic will fall.

natural variability: The variability of any specific material quality characteristic measurement data resulting from natrual random variation in composition and/or placement processing.

nonrandom error: Difference between a measured value and its true value due to a significant, consistent, assignable cause.

observation: An act of recognizing and noting some fact or occurrence. The act of seeing or fixing the mind on something.

one hundred percent inspection: Inspection of each and every unit of material or work in a construction block; screening.

parameter: A quantity conveniently used for indirectly measuring a variable property of a material or any other statistical population.

permittee: The holder of a permit to construct and operate a hazardous waste disposal facility, i.e., the owner or operator.

population: The total set of possible measurements of any quality characteristic. See also Universe.

precision: The degree of mutual agreement among individual measurements of a consistent material made under prescribed, like conditions.

process control: A procedure whereby construction equipment, processes, and operations are continually inspected to yield a product conforming with project specifications, together with procedures for correcting unacceptable materials or work. See also Quality Control, Control of Quality.

profile: The vertical arrangement of soil layers.

quality: The level of performance of a product, a construction process, or a construction block, measured in terms of specified requirements.

quality assurance: The planned and systematic actions necessary to provide adequate confidence that a structure or a system will perform satisfactorily in service, i.e., in accordance with design requirements.

quality characteristic: A physical or chemical property or any other requirement used to define the nature of a product or process.

quality control: See Control of Quality; Process Control.

quality personnel management: The implementation of management practices to effect worker involvement in quality assurance.

random error: A difference between a measured value and the true value that appears to occur without aim, reason, or cause, depending only on chance.

random sample: A sample in which each of the sample units has been selected at random from the construction block.

repeatability, reproducibility: A special purpose designation of precision for particular operations that require specific definitions for each use. Repeatability is customarily used to designate precision for measurements made within a very restricted set of conditions (for example, individual operators), while reproducibility is customarily used to designate precision for measurements involving variation between certain sets (for example, laboratories) as well as within them. (ASTM Designation E 456-72).

replicate samples: A series of more than two samples taken from the same block.

representative sample: A sample without bias; a true sample; a sample whose quality is the "average" of the block.

sample: A collection of units of increments, usually chosen at random from a construction material, a construction process block, or an incoming shipment, to represent the whole.

sample increment: The portion of material removed (or tested in place) from a sample unit selected at random from a block during sampling. See also Increment.

sample unit: A small part of a construction block. It is assumed that variations within the unit are random, i.e., due to chance.

screening: See One Hundred Percent Inspection.

soil index properties tests: These are physical tests of soils yielding numerical results known as index properties.

specification: The detailed quality characteristics which a material or process is required to fulfill.

standard deviation: A measure of variability of data about the average, or mean, value; the square root of the mean of the sum of the squares of the individual deviation from the mean.

stratified random sample: A random sample in which increments are taken at random from each of the several strata, or sub-blocks, of the larger block, or population.

systematic error: A constant error, in one direction, which causes the average of a number of measurements to be offset from the true or reference value; see also Accuracy, Bias Error.

systematic sampling with random start: A random sample in which the first sample unit is chosen at random and successive units are selected at uniform intervals of time, distance, area, or volume.

test: An act or process that reveals inherent qualities; usually involving a specific and consistent technique and often a specific piece of test equipment.

test portion: The part of a sample actually tested; usually obtained by reduction of sample increments by random methods.

turnkey contractor: An individual or organization that contracts with an owner to design, construct, and, usually, initially operate a facility.

uniform random sample: A random sample in which every sample unit within the block, or population, has an equal chance of being selected.

universe: The total set of possible measurements of any quality characteristic. See also Population.

variance: The square of the standard deviation; a measure of variability of data about the mean, or average; the mean of the sum of the squares of the individual deviations from the mean.

APPENDIX B

TEST METHOD DESCRIPTIONS

The descriptions presented in Appendix B are only intended to give the reader general information about the specific test methods. More detailed information can be obtained from the references noted for the various test methods. Data sheets for some of the test methods are provided as illustrative examples. These data sheets are merely examples and their inclusion here does not connote that the authors recommend that they specifically be used.

APPENDIX B

Method	Number
Parameter Measured: Water Content	
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Method No. 1

Parameter Measured: Water Content

Title of Test Method: Standard Oven-Dry

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried in an oven.

Test Method

(1) Apparatus: Drying oven (thermostatically controlled, preferably of the force-draft type), balance sensitive to 0.01 g., specimen containers (tares) with lids, and a desiccator.

(2) Procedure: The procedure for this method consists simply of taking a specimen of known weight, placing it into an oven and drying it at a particular temperature and specified time. Upon drying the specimen is removed, reweighed and the moisture content is calculated.

(3) Reference: ASTM D 2216.

Limitations: With many soils, close control of water content during field compaction is necessary to develop a required density, strength and hydraulic conductivity in the soil mass. Oven-drying is the standard test for determining water content of soils in the geotechnical engineering practice. However, the method does not lend itself easily to field use. Although temperature controlled ovens are currently available on some construction sites, they require 4 to 12 hours for drying which may be excessive for the close control of field compaction. All soils can be tested for moisture content by oven-drying.

Status of the Method: Oven-drying of soil is the accepted laboratory method among the geotechnical engineering profession for determination of water content.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. An example data sheet is provided.

Name:______________________________ Sample Numbers______________________________

Date:______________________________ Sheet Number ______________________________

WATER CONTENT DETERMINATIONS
DATA AND COMPUTATION SHEET

NOTES: Tare is weight of container (watch glasses and clip, Petri dishes, can, etc.)

$$\text{Water Content} = w = \frac{\text{Wt. of Water}}{\text{Wt. of Dry Soil}} \cdot 100\%$$

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

Sample Number						
Type of Test						
Container Number						
Wt. Sample + Tare Wet						
Wt. Sample + Tare Dry						
Wt. of Water						
Tare						
Wt. of Dry Soil						
Water Content						

Method No. 2

Parameter Measured: Water Content

Title of Test Method: Standard Nuclear Moisture/Density Gage

Principle of Test Method: This method measures in place water content by directing fast neutrons of known intensity into the soil and measuring the intensity of slow or moderated neutrons reflected back.

Test Method

(1) Apparatus: Fast neutron source, slow neutron detector (readout device and housing) and reference standard and site preparation device.

(2) Procedure: This method allows the determination of water content of soil and soil aggregate in place through the use of nuclear equipment. The equipment is calibrated to determine water content, as weight of water per unit volume of material. Water content as normally used is defined as the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles. It is determined with this procedure by dividing the water content by the dry unit weight of the soil. Therefore, computation of water content using the nuclear equipment also requires the determination of the dry unit weight of the material being tested. Most available nuclear equipment has the provision for measuring both the water content and the wet unit weight. The difference between these two measurements gives the dry unit weight.

(3) Reference: ASTM D 3017.

Limitations: The method described is useful as a rapid, nondestructive technique for the in-place determination of the water content of soil. The fundamental assumptions inherent in the method are that the hydrogen present is in the form of water as defined by ASTM D 2216, and that the material under test is homogeneous. Test results may be affected by chemical composition, sample heterogeneity, and, to a lesser degree, material density and the surface texture of the material being tested. The technique also exhibits spatial bias in that the apparatus is more sensitive to certain regions of the material under test. The nuclear method, which is applicable to a wide range of soils, requires operation by an experienced technician in order to obtain reliable measurements. A weakness in the nuclear method is that a sample is not taken to determine the water content, and thus the test results cannot be compared to the other water content methods, e.g. the oven-dry method. In addition, this method requires equipment that utilizes radioactive materials which themselves may be hazardous to the health of the operator. Effective operator instructions together with routine safety procedures are essential to the proper operation of this type of equipment.

Status of the Method: Nuclear gages offer a rapid and accurate means for obtaining water content values for a wide variety of soils. Recent advances in the design of nuclear equipment and a better understanding of the nuclear principles involved have led to increasingly widespread use of nuclear gages in earthwork construction control.

Calibration Procedure: The apparatus must be calibrated against a reliable direct method (e.g. oven-drying).

Documentation of Test: Items to be recorded include the water content and the wet unit weight. An example data sheet is provided.

DATA SHEET FOR FIELD DENSITY TEST
NUCLEAR GAUGE METHOD

A	Moisture Standard Count		Gauge Type	Serial No.
B	Density Standard Count			

FOR

JOB	JOB NO.
SOURCE OF MATERIAL	DATE

	TEST LOCATION							
	ELEVATION							
	TEST NUMBER							
C	Moisture Count							
D	Moisture Count Ratio	$\frac{C}{A}$						
E	Density Count							
F	Air-Gap Count (if used)							
G	Density Count Ratio	$\frac{E}{B}$ or $\frac{E}{F}$						
H	Density, Wet Wt., PCF	From G & Chart						
I	Moisture Content, PCF	From D & Chart						
J	Density, Dry Wt., PCF	H - I						
K	MOISTURE CONTENT, PERCENT	$\frac{I}{J}$						
L	OPTIMUM MOISTURE, PERCENT	See Curve						
M	DENSITY, DRY WT., PCF	From J						
N	THEORETICAL DENSITY, PCF	See Curve						
O	PERCENT COMPACTION	$\frac{M}{N}$ x 100						
P	REQUIRED PERCENT COMPAC.	See Specs.						
Q	MODE & PROBE DEPTH, IN.							
R	TYPE OF MATERIAL							

Laboratory No.	Technician(s)

Parameter Measured: Water Content

Title of Test Method: Gas Burner

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried.

Test Method

(1) Apparatus: Gas stove, frying pan, balance and stirring rods.

(2) Procedure: This method determines the approximate water content of soils by means of a gas-burner stove. The gas burner method involves the weighing of a moist sample, placing the sample in a pan on the stove and drying it to a constant weight, with occasional stirring of the sample to prevent burning. The dry sample, first permitted to cool, is then reweighed and the water content is determined.

(3) Reference: N/A

Limitations: The gas-burner method is used extensively for testing gravelly material. Two or more samples may be tested concurrently. When care is exercised to prevent overheating or burning of the sample, the testing time is usually about 1/2 hour. The method is inaccurate for organic soils or for those soils containing particles with loosely bound water, unless the drying time is accomplished at a temperature of not more than 140°F (60°C) for 1 hour or longer.

Status of the Method: The gas-burner method is used extensively as a rapid method for testing gravelly soils in the field control of earthwork.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Method No. 4

Parameter Measured: Water Content

Title of Test Method: Alcohol Burning

Principle of Test Method: This method determines the water content of a soil sample by first weighing it wet and then again after it has been dried by alcohol burning.

Test Method

(1) Apparatus: Metal pan, balance, denatured alcohol and stirring rods.

(2) Procedure: This method determines the approximate water content of soil by burning alcohol that has been added to the soil. The general procedure consists of placing a weighted quantity of moist soil in a pan, adding alcohol to it and stirring the mixture, then igniting the alcohol. After ignition and the complete removal of the moisture by burning, the sample is reweighed and its water content is calculated.

(3) Reference: N/A

Limitations: The alcohol burning test is a rapid inexpensive method for determining the water content of soils. The method is usable with non-cohesive and cohesive soils. The method should not be used if the soil contains a large proportion of clay, gypsum, calcareous matter or organic matter. A large quantity of alcohol is required for testing coarse gravelly material. For multiple burnings, the testing time can be in excess of 1/2 hour. In terms of safety, the alcohol burning test possesses the potential for fire. Care should be exercised not to have alcohol on hand or in an open storage container near the testing apparatus during the ignition phase of the test. The alcohol should be stored in a safety container.

Status of the Method: The alcohol burning method of obtaining the water content of soil in the field has provided satisfactory results. Its use in the field has been well established.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Method No. 5

Parameter measured: Water Content

Title of Test Method: Calcium Carbide (Speedy)

Principle of Test Method: This method determines the water content of a soil sample by measuring the pressure developed when measured quantities of the soil sample and powdered calcium carbide are mixed.

Test Method

(1) Apparatus: Calcium carbide pressure moisture tester, tared scale, two each 1-1/4 in. steel balls, brush, cloth and scoop.

(2) Procedure: The calcium carbide gas pressure method for determining water content consists of mixing measured quantities of moist soil and powdered calcium carbide in a closed chamber and measuring the pressure developed by the formation of acetylene gas. The reaction of calcium carbide and water forms acetylene gas and calcium hydroxide. The pressure developed is directly related to the amount of water entering into the reaction.

(3) Reference: AASHTO T 217.

Limitations: Only two sizes of testers are commercially available to test for water content using this method: (1) 26 gram capacity model and (2) a six-gram capacity model. The small chamber capacities of these devices control the soil sample size to be used. As a result, this method is unsuitable for representative samples of coarse granular material. AASHTO T 217 recommends that this method should not be used on granular material having particles large enough to affect the accuracy of the test (i.e. a soil with a grain-size distribution such that an appreciable amount would be retained on 4.75 mm sieves). If a six-gram sample is used (according to AASHTO T 217), the sample should not contain any particles that will be retained on the 2.00 mm sieve. The testing of heavy clays with this method requires special handling.

Status of the Method: The apparatus for this method is relatively inexpensive and well adapted to field testing. Use in the United States is extensive. In the field the calcium carbide method has been used extensively in the control of embankment construction. Normal testing time is less than 10 min. A moderate amount of operator training is required. The calcium carbide method is a standard method for rapid water content determination referenced under AASHTO.

Calibration Procedure: A calibration curve is required.

Documentation of Test: Items to be recorded include soil sample weight, powdered calcium carbide weight and the resultant gas pressure. No example data sheet is provided.

Parameter Measured: Water Content

Title of Test Method: Microwave Oven

Principle of Test Method: This method determines the water content of a soil by first weighing it wet and then again after it has been dried in the oven.

Test Method

(1) Apparatus: Microwave oven suitable for drying, balance, specimen containers.

(2) Procedure: The procedure for this method is the same as that for the Standard Oven-Dry method. That is, a specimen is placed wet onto a balance and weighed. It is then placed in a microwave oven and dried completely. It is then weighed again. The weight difference was the water content.

(3) Reference: N/A

Limitations: Microwave ovens are not noted for their drying ability. There are necessary safety precautions when using a microwave oven.

Status of the Method: This method is not commonly used. Although a microwave oven heats much more rapidly than a conventional oven, it is an erratic dryer at best. Thus this method should probably only be used to determine water contents for soils which can be expected to have a low value, i.e. relatively low water content.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Method No. 7

Parameter Measured: Water Content

Title of Test Method: Infrared Oven

Principle of Test Method: This method determines the water content of a soil by first weighing it wet and then again after it has been dried in the oven.

Test Method

(1) Apparatus: Infrared oven suitable for drying, balance, specimen containers.

(2) Procedure: The procedure for this method is the same as that for the Standard Oven-Dry method. That is, a specimen is placed wet onto a balance and weighed. It is then placed in an infrared oven and dried completely. It is then weighed again. The weight difference was the water content.

(3) Reference: N/A

Limitations: There are necessary safety precautions when using an infrared oven. Infrared ovens are generally not widely available.

Status of the Method: This method is not commonly used. It can yield rapid results, however. The method should be desirable to a large operation where the benefits of rapid results outweigh the costs of the limitations above and the initial investment.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the wet weight and the dry weight. No example data sheet is provided.

Method No. 8

Parameter Measured: Unit Weight

Title of Test Method: Standard Laboratory Volumetric

Principle of Test Method: This method determines the unit weight of an undisturbed soil sample by measuring its weight and volume.

Test Method

(1) Apparatus: Sampling tools, balance, water bath, volume measuring device, oven and coating material (e.g. paraffin).

(2) Procedure: This method determines the density of cohesive soil in its natural state, compacted cohesive soil, and stabilized soil by measuring the weight and volume of undisturbed samples. The method briefly consists of cutting out a block of soil, coating it with a known amount of paraffin, weighing to obtain the net weight of the sample and immersing it in an overflow volumeter to determine the net volume of the sample, then dividing through for the unit weight.

(3) Reference: AASHTO T 233.

Limitations: The method is suitable for any material that remains intact during sampling. This metod is particularly adaptable to irregularly shaped specimens and soil containing gravel shells, etc. Sample size is not limited; large samples with coarse aggregate can be tested. This method is time consuming.

Status of the Method: This method is a nonstandard test when used in relation to compaction control. However, periodic record sampling on compacted embankments for dams usually entails obtaining block samples. In addition, if the sample is properly removed from the fill, this test provides for index and engineering properties.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the sample's net weight and net volume. An example data sheet is provided.

ORDER NO.__________

CLIENT'S NO.__________

DATE__________

UNIT WEIGHTS

PROJECT__________ **LOCATION**__________ **TESTED BY**__________

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS $(W_w=w-w')$						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS $(W_s=w'-w'')$						
% MOISTURE, $(W_p=W_w/W_s\times100)$						
DRY UNIT WT. LBS./FT.^{3}						

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS $(W_w=w-w')$						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS $(W_s=w'-w'')$						
% MOISTURE, $(W_p=W_w/W_s\times100)$						
DRY UNIT WT. LBS./FT.^{3}						

SAMPLE NO.						
ORIGINAL SAMPLE SIZE						
WT. CONTAINER + WET SOIL, GRAMS (w)						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. MOISTURE, GRAMS $(W_w=w-w')$						
WT. CONTAINER + DRY SOIL, GRAMS (w')						
WT. CONTAINER, GRAMS (w'')						
WT. DRY SOIL, GRAMS $(W_s=w'-w'')$						
% MOISTURE, $(W_p=W_w/W_s\times100)$						
DRY UNIT WT. LBS./FT.^{3}						

____

Parameter Measured: Unit Weight

Title of Test Method: Standard Laboratory Displacement

Principle of Test Method: This method determines the unit weight of a soil sample by determining the weight of the sample and the volume of its hole.

Test Method

(1) Apparatus: Sampling tools, soil tray and pans, balances, measure, drying equipment, two gallons of lubricating oil, and a gauge point.

(2) Procedure: This method determines the density of soil in-place by finding the mass and water content of a disturbed sample and measuring the volume occupied by the sample using an oil of a known density. The method can be performed fairly fast, however a chief concern is the mess caused by the oil. The general procedure consists of leveling the test site, digging a hole in the compacted earthwork, weighing the material removed, measuring the volume of the hole by placing a measured quantity of oil in it and calculating the wet unit weight by dividing the weight of the moist soil by the volume of the hole.

(3) Reference: AASHTO T 214.

Limitations: This method may be used in testing materials with both fine and coarse particles; however, the test is best suited for soils and soil-aggregate mixtures that are relatively impervious. The method may not be suitable for testing materials having fissures, cracks, or large voids.

Status of the Method: The oil displacement method is a conventional test in the control of earthwork construction. However, it often provides less satisfactory results than the sand-cone method.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of the oil. No example data sheet is provided.

Parameter Measured: Unit Weight

Title of Test Method: Standard Field Sand-Cone

Principle of Test Method: This method determines unit weight by determining the weight of a soil sample and the volume of its hole.

Test Method

(1) Apparatus: One gallon jar, double cone assembly, base plate and accessories.

(2) Procedure: The test consists of digging out a sample of the material to be tested and weighing it. The volume of the hole is then determined by using the sand-cone.

(3) Reference: ASTM D 1556.

Limitations: The sand-cone has features which limit its usefulness. The method can be used satisfactorily, however, if these limitations are recognized and proper precautions observed. The poured density of sand is affected by atmospheric moisture and changes in relative humidity which means the sand should be calibrated before use. Care should be exercised to avoid jarring and densifying the sand during the filling procedure and the test should not be conducted during vibration of the site such as occurs during the use of heavy equipment. Sample size is limited by sand supply.

Status of the Method: The sand-cone test is a conventional test method for earthwork control. The method is reliable and the most commonly used test to determine the density of in-place soil. On Corps of Engineers earthwork projects the test serves as the referee test for all other control tests used. The sand-cone test is widely used in cohesive soils and can be also used in soils that are of low plasticity as well as gravelly soils. The test is not applicable in clean sands or gravel and loose granular material. The method is applicable to large and small projects.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of the sand. No example data sheet is provided.

Method No. 11

Parameter Measured: Unit Weight

Title of Test Method: Standard Field Rubber Balloon

Principle of Test Method: This method determines unit weight by determining the weight of a soil sample and the volume of its hole.

Test Method

(1) Apparatus: Calibrated vessel, elastic membrane, pressure control device, baseplate and accessories.

(2) Procedure: This method determines the in-place density by removing soil from a hole, weighing the excavated material, and measuring the volume of the hole by a liquid-filled (water) balloon under constant pressure. Chief advantages of this method are its operation simplicity and speed with which tests can be conducted.

(3) Reference: ASTM D 2167.

Limitations: For general use in clays and consolidated sands, the rubber balloon apparatus provides good results. The method is not suitable for very soft soil which will deform under slight pressure or in which the volume of the hole cannot be maintained constant. The method is not well adapted to the measurement of volumes in loose granular material. However, of all in-place density tests some soil engineers recommend the water balloon as the preferred method for granular soils. The tests is well adapted to small and large projects. Physical limitation of the apparatus restricts the size of the test hole to approximately four or six inches in diameter and from six to twelve inches in depth.

Status of the Method: The water balloon test is widely used for determining in-place density for the control of earthwork. The method is used by the Corps of Engineers and other agencies because of its application to a wide range of materials and its past performance record.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the weight of the soil sample and the volume of water. No example data sheet is provided.

Method No. 12

Prameter Measured: Unit Weight

Title of Test Method: Standard Field Drive-Cylinder

Principle of Test Method: This method determines the unit weight of a soil sample by securing one in a known-volume tube and then weighing it.

Test Method

(1) Apparatus: Acceptable drive cylinder, drive head, straightedge, shovel, weight, scales, drying oven and airtight containers.

(2) Procedure: The drive-cylinder method for determining in-place density involves obtaining a relatively undisturbed soil sample by driving a thin-walled cylinder into the soil with a special driving head. Two procedures are described in ASTM D 2937 for performing this test, one for testing at the surface or at very shallow depths, usually less than 3 ft (1 m), and one for testing at greater depths. The general procedure for both depths consists of driving a sampling tube into the soil, withdrawing the tube with the sample, trimming the sample flush with the ends of the tube, weighing, then calculating the unit weight of the soil by dividing the net weight of the sample by the volume of the tube.

(3) Reference: ASTM D 2937.

Limitations: The drive-cylinder method of determining in-place density can be used satisfactorily in moist, cohesive, fine-grained soils and in many sands which exhibit tendencies toward cohesiveness. The method is not appropriate for sampling very hard soils which cannot be penetrated easily, or for soils of low plasticity which are not readily retained in the cylinder. The method sample size is limited by the sample tube. The chief disadvantage of the test is that it is limited to fine-grained soils.

Status of the Method: The standard field drive-cylinder method is a conventional test method in earthwork control. It is, however, less accurate than the sand cone or water balloon methods.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the soil sample's weight. No example data sheet is provided.

Method No. 13

Parameter Measured: Unit Weight

Title of Test Method: Standard Nuclear Moisture/Density Gage

Principle of Test Method: This method determines unit weight by a gamma source and a gamma detector.

Test Method

(1) Apparatus: A nuclear source emitting gamma rays, a gamma ray detector and a counter.

(2) Procedure: This method determines the density of soil and soil-aggregate in place through the use of nuclear equipment. In general, the total or wet density of the material under test is determined by placing a gamma source and a gamma detector either on, into, or adjacent to the material under test. These variations in test geometry are presented as the backscatter, direct transmission, or air gap approaches. The intensity of radiation detected is dependent in part upon the density of the material under test. The radiation intensity reading is converted to measured wet density by a suitable calibration curve. Some commonly used sources of gamma rays are radium, cobalt 60 and cesium 137.

(3) Reference: ASTM D 2922.

Limitations: The method described is useful as a rapid, nondestructive technique for the in-place determination of the wet density of soils and soil-aggregates. The fundamental assumptions inherent in the method are that Compton scattering is the dominant interaction and that the material under test is homogeneous. Test results may be affected by chemical composition, sample heterogeneity, and the surface texture of the material being tested. The technique also exhibits spatial bias in that the apparatus is more sensitive to certain regions of the material under test. The nuclear method is applicable to a wide range of soil. The nuclear method requires a considerably experienced operator in order to obtain reliable measurements. A weakness in the nuclear method is that a sample is not taken to determine the water content, and thus the test results cannot be compared to another unit weight method. In addition this method requires equipment that utilizes radioactive materials which may be hazardous to the health of the operator. Effective operator instructions together with routine safety procedures are essential to the proper operation of this type of equipment.

Status of the Method: Nuclear gages offer a rapid and accurate means of obtaining density values for a wide variety of materials. Recent advances in the design of nuclear equipment and a better understanding of the nuclear principles involved have led to increasingly widespread use of nuclear gages in earthwork construction control.

Calibration Procedure: The apparatus must be calibrated against a reliable direct method (e.g. standard field sand-cone).

Documentation of Test: Items to be recorded include the counter's gamma ray counts. No example data sheet is provided.

Method No. 14

Parameter Measured: Specific Gravity

Title of Test Method: Standard Laboratory

Principle of Test Method: This method determines the specific gravity of a soil sample by the use of a pycnometer.

Test Method

(1) Apparatus: A pycnometer and a balance.

(2) Procedure: The procedure for this method is to procure a soil sample, weigh it with the balance, and then determines its specific gravity by the use of the pycnometer.

(3) ASTM D 854.

Limitations: N/A

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the sample weight and the pycnometer reading. An example data sheet is provided.

Name: ______________________________ Sample Numbers ______________________

Date: ______________________________ Sheet Number ______________________

SPECIFIC GRAVITY DETERMINATIONS

Sample Number ______________ Date: ______________

Pycnometer Bottle Number: ______________ Evap. Dish No. ______________

Wt. Bottle + Water + Sample $= W_s =$ ______ Wt. Sample + Dish Dry = ______

Temperature of Suspension $= T =$ ______ Weight of Dish = ______

Wt. Bottle + Water at temp. $T = W_w =$ ______ Dry Wt. of Soil W_o = ______

$s = \frac{W_o}{W_o + W_w - W_s}$ = ______________ = ________ = ____________

Remarks: ____

Sample Number ______________ Date: ______________

Pycnometer Bottle Number: ______________ Evap. Dish No. ______________

Wt. Bottle + Water + Sample $= W_s =$ ______ Wt. Sample + Dish Dry = ______

Temperature of Suspension $= T =$ ______ Weight of Dish = ______

Wt. Bottle + Water at temp. $T = W_w =$ ______ Dry Wt. of Soil W_o = ______

$s = \frac{W_o}{W_o + W_w - W_s}$ = ______________ = ________ = ____________

Remarks: ____

Sample Number ______________ Date: ______________

Pycnometer Bottle Number: ______________ Evap. Dish No. ______________

Wt. Bottle + Water + Sample $= W_s =$ ______ Wt. Sample + Dish Dry = ______

Temperature of Suspension $= T =$ ______ Weight of Dish = ______

Wt. Bottle + Water at temp. $T = W_w =$ ______ Dry Wt. of Soil W_o = ______

$s = \frac{W_o}{W_o + W_w - W_s}$ = ______________ = ________ = ____________

Remarks: ____

Method No. 15

Parameter Measured: Grain-Size Distribution

Title of Test Method: Standard Sieve Analysis (+200 Fraction)

Principle of Test Method: This method determines the +200 fraction of a soil sample by the use of a No. 200 sieve.

Test Method

(1) Apparatus: A No. 200 sieve, that is a sieve with 200 openings per square inch, and balance.

(2) Procedure: This is a method dependent test. A dried soil sample is weighed and poured onto a No. 200 sieve and shook. That amount of soil not passing through the sieve is the +200 fraction. The +200 fraction is then weighed on the balance.

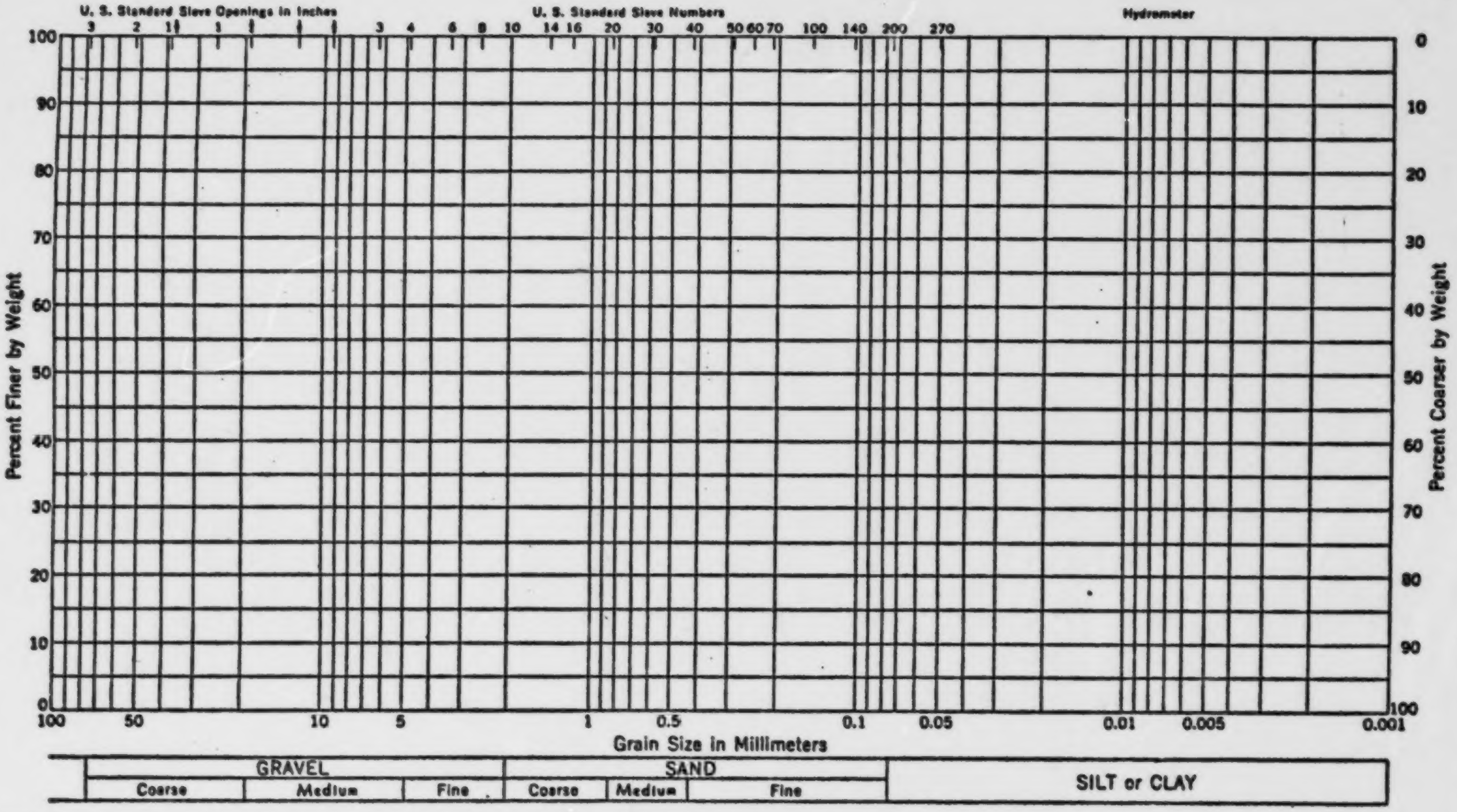
(3) Reference: ASTM D 422.

Limitations: The limitations of the method are its possible sources of error. These include: (a) overloading the sieve; (b) inadequate or incorrect shaking; and (c) broken or damaged sieves.

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the weight of the dried soil sample and the weight of the +200 fraction. An example data sheet is provided.



SAMPLE NO.	W.C.	LL	PL	PI	CLASSIFICATION

DRAWN	APPROVED	DATE	JOB No.

Method No. 16

Parameter Measured: Grain-Size Distribution

Title of Test Method: Amount of Soil Finer than No. 200 Screen (Wash)
Standard

Principle of Test Method: This method determines the -200 fraction of a soil sample by the use of a No. 200 sieve and washing.

Test Method

(1) Apparatus: A No. 200 sieve and a balance.

(2) Procedure: This method is similar to that described for determining the +200 fraction. However if the soil sample to be tested contains plastic fines, drying will cause them to adhere to the fine sand grains, and the test will yield erroneous results. The solution is to weigh the dry sample beforehand. Pour it on the No. 200 screen. Wash the sample to loosen the fines and allow them to pass through the sieve. Dry that amount of soil remaining on the No. 200 screen and weigh it. The two weight differences is then the fines content.

(3) Reference: ASTM D 422.

Limitations: The significant limitation of this method is the extra time required for washing and redrying.

Status of the Method: This is the standard method. It is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample and the dry weight of the +200 fraction. No example data sheet is provided.

Parameter Measured: Grain-Size Distribution

Title of Test Method: Standard Laboratory Hydrometer (-200 Fraction)

Principle of Test Method: This method determines the grain-size distribution of the -200 fraction of a soil sample by the use of Stokes' Law and a standardized hydrometer.

Test Method

(1) Apparatus: A No. 200 sieve, a standardized hydrometer, a sedimentation cylinder, a thermometer and a breaker.

(2) Procedure: This method determines the grain-size distribution of that fraction of a soil sample passing the No. 200 sieve (the -200 fraction). The method utilizes a deflocculating (dispersing) agent and Stokes' Law to enable the different particle sizes to settle at different rates, thus enabling the technician to determine their distribution.

(3) Reference: ASTM D 422.

Limitations: An experienced technician is required to perform this test method. Considerable time is required for sample preparation. The test itself requires several hours to perform.

Status of the Method: This is the standard method. As it is the only "exact" method for determining the percent silt sizes and the percent clay sizes, it is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample and the dry weights of the settled fractions. Example data sheets are provided.

Name:______________________________ Sample and Test Number____________________

Date:______________________________ Sheet Number____________________

HYDROMETER ANALYSIS
DATA AND COMPUTATION SHEET

Evaporating Dish No. ________________

Wt. Sample + Dish Dry = ________________

Wt. Dish = ________________

Dry Wt. W_o = ________________

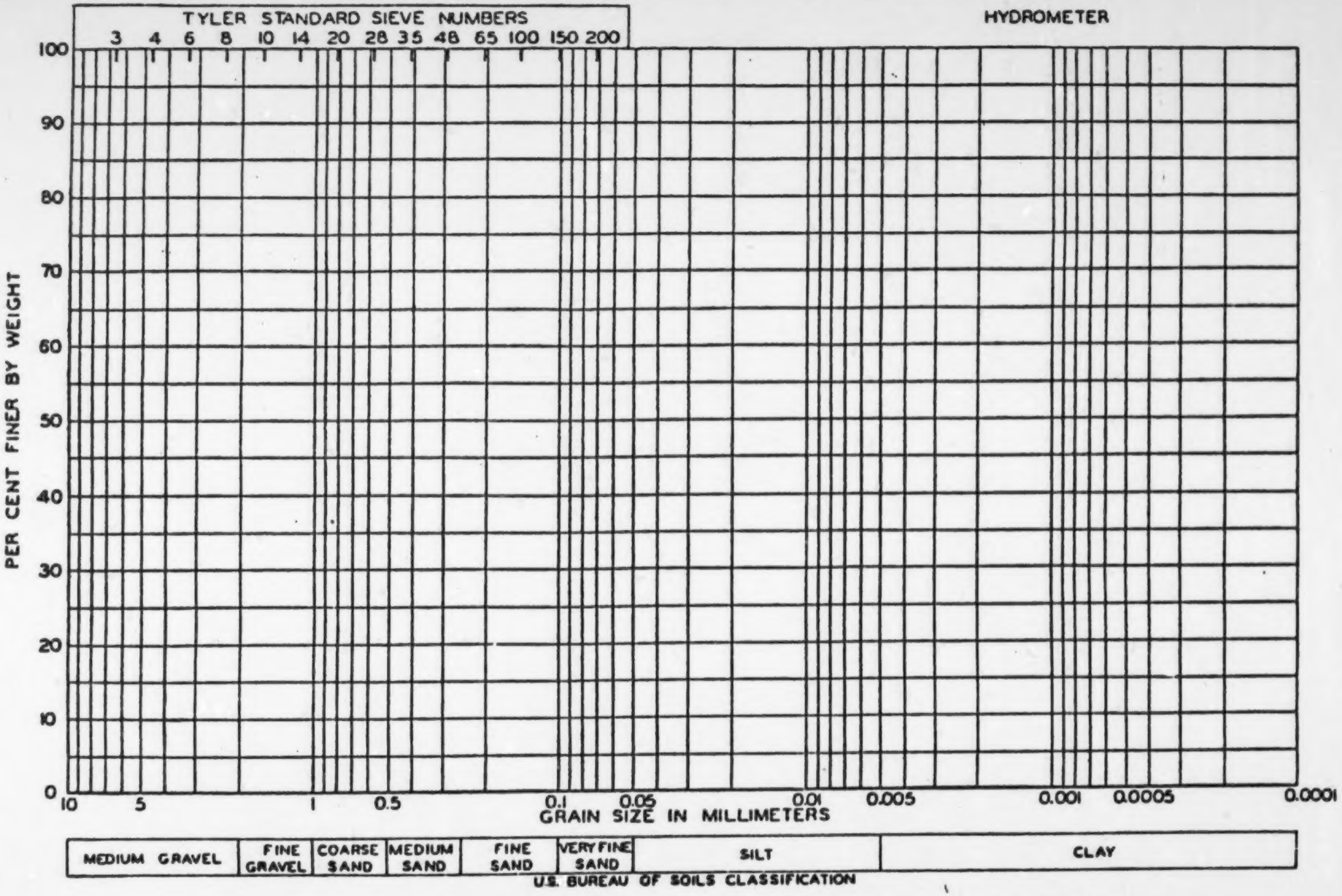
$$W\% = \frac{100}{W_o}\,\frac{s}{s-1}\,(R + m)$$

$$W\% = \frac{100}{}\;\underline{}\;(R + m)$$

$$W\% = \underline{}\,(R + m)$$

Hydrometer Number____________________ Meniscus Correction = c = ________________

Date	Time	Temp.	Elapsed Time	R'	R=R'+c	Grain Diam	R + m	W%	Remarks



PROJECT__________ BORING NO __________ SAMPLE NO. __________

DEPTH______ ELEVATION______ REMARKS__________

GRAIN SIZE DISTRIBUTION DIAGRAM

Method No. 18

Parameter Measured: Grain-Size Distribution

Title of Test Method: Pipette Method for Silt and Clay Fraction

Principle of Test Method: This method determines the silt and clay fractions of a soil sample by the use of a dispersing agent, Stokes' Law and a Pipette.

Test Method

(1) Apparatus: A No. 200 sieve, a beaker and a pipette.

(2) Procedure: The soil sample is deflocculated in a dispersing agent for one hour. The soil-water-agent mixture is then agitated and allowed to sit. Theroretically all the sand and silt sizes will have settled by then. The water, with the suspended clay sizes, is then drawn off by the pipette. The settled fraction is the original soil sample minus the clay fraction. The settled fraction is completely dried and passed through a No. 200 sieve. The fraction passing is the silt fraction, the fraction remaining is the sand fraction.

(3) Reference: Mills, 1970.

Limitations: The method is less exact than the standard laboratory hydrometer method.

Status of the Method: The method lends itself well to field laboratory use and is widely accepted.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weight of the sample, the dry weight of the settled fraction and the dry weight of the silt fraction. No example sheet is provided.

Parameter Measured: Grain-Size Distribution

Title of Test Method: Decantation Method for Silt and Clay Fraction

Principle of Test Method: This method determines the silt and clay fractions of a soil sample by the use of a dispersing agent, Stokes' Law and decantation.

Test Method

(1) Apparatus: A No. 200 sieve and a beaker.

(2) Procedure: The soil sample is deflocculated in a dispersing agent for one hour. The soil-water-agent mixture is then agitated and allowed to sit. Theoretically all the sand and silt sizes will have settled by then. The water, with the suspended clay sizes, is then drawn off by decantation (careful pouring). The settled fraction is the original sample minus the clay fraction. The settled fraction is completely dried and passed through a No. 200 sieve yielding the silt fraction.

(3) Reference: Mills, 1970.

Limitations: The method is less exact than the standard laboratory hydrometer method. As is also more rudimentary than the pipette method, it can be less accurate than this method in execution.

Status of the Method: The method lends itself well to field laboratory use and is widely accepted.

Calibration Procedure: N/A

Documentation of Test: Items to be documented include the dry weights of the sample, the settled fraction and the silt fraction. No example sheet is provided.

Parameter Measured: Liquid Limit

Title of Test Method: Standard Multipoint

Principle of Test Method: This method determines the liquid limit of a soil sample by the use of the liquid limit device and a minimum of three trials.

Test Method

(1) Apparatus: Evaporating dish, spatula, liquid limit device, grooving tool and balance.

(2) Procedure: A soil sample is oven dried. Distilled water is added and mixed thoroughly with the sample till it is ready to be tested. A sample is placed in the liquid limit device and divided by the grooving tool. The test is run till the soil halves meet. The result is plotted. A minimum of three trials are performed.

(3) Reference: ASTM D 423.

Limitations: The method requires considerable time and a laboratory environment to be performed.

Status of the Method: For the purposes needed at a hazardous waste disposal facility the standard one point method will yield reasonable data with less effort and hence is more widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry weight of the sample, the water content and the number of blows. An example data sheet is provided.

ATTERBERG LIMITS DETERMINATION

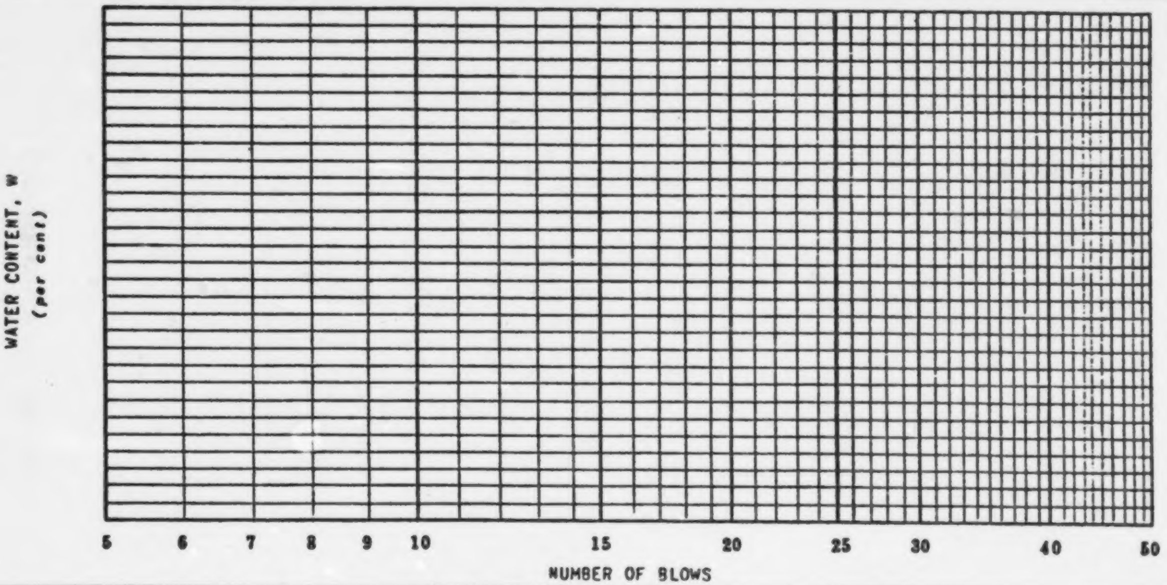
PROJECT	EXCAVATION NUMBER	SAMPLE NUMBER

DATE

LIQUID LIMIT, w_l

RUN NUMBER						
TARE NUMBER						
A. WEIGHT OF WET SOIL + TARE						
B. WEIGHT OF DRY SOIL + TARE						
C. WEIGHT OF WATER, W_w (A.-B.)						
D. WEIGHT OF TARE						
E. WEIGHT OF DRY SOIL, W_s (B.-D.)						
WATER CONTENT, $w = (\frac{W_w}{W_s} \times 100)$						
NUMBER OF BLOWS						

w_L	w_P	I_P (w_L-w_P)



PLASTIC LIMIT, w_P

					NATURAL WATER CONTENT
RUN NUMBER					
TARE NUMBER					
F. WEIGHT OF WET SOIL + TARE					
G. WEIGHT OF DRY SOIL + TARE					
H. WEIGHT OF WATER, W_w (F.-G.)					
I. WEIGHT OF TARE					
J. WEIGHT OF DRY SOIL, W_s (G.-I.)					
WATER CONTENT, $w = (\frac{W_w}{W_s} \times 100)$					
PLASTIC LIMIT, I_P (Average w)					

REMARKS

TECHNICIAN (*Signature*)	COMPUTED BY (*Signature*)	CHECKED BY (*Signature*)

DD FORM 1 AUG 57 1209

GPO-831409

Method No. 21

Parameter Measured: Liquid Limit

Title of Test Method: Standard One Point

Principle of Test Method: This method determines the liquid limit of a soil sample by the use of the liquid limit device and one trial.

Test Method

(1) Apparatus: Evaporating dish, spatula, liquid limit device, grooving tool and balance.

(2) Procedure: A soil sample is oven dried. Distilled water is added and mixed thoroughly with the sample till it is ready to be tested. A sample is placed in the liquid limit device and divided by the grooving tool. The test trial is then run till the soil halves meet. The data is then plotted.

(3) Reference: ASTM D 423.

Limitations: The method requires considerable time and a laboratory environment to be performed.

Status of the Method: The method is more widely used than the standard multipoint method, but as it is a correlation test method and it is usually used in soil identification, it is often less practical than the commonly used visual-manual procedure (ASTM D 2488).

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry weight of the sample, the water content and the number of blows. No example data sheet is provided.

Parameter Measured: Plastic Limit

Title of Test Method: Standard Laboratory

Principle of Test Method: This method determines the plastic limit of a soil sample, that is the lowest water content at which the soil can be rolled into 1/8 in. threads without breaking.

Test Method

(1) Apparatus: Evaporating dish, spatula, suitable containers, and balance.

(2) Procedure: For a given soil sample begin at a water content estimated to be greater than that at the plastic limit. A good start point would be the approximate liquid limit. Shape the soil into an ellipsoidal mass. Roll the sample into 1/8 in. threads. Cut the threads into 6 to 8 pieces. Repeat the process till the threads break at 1/8 in. An oven-dry moisture content determination at that point will yield the plastic limit.

(3) Reference: ASTM D 424.

Limitations: The method is simple and straightforward.

Status of the Method: This is the standard method and is widely used.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the oven-dry and wet weight of the sample at the plastic limit. An example data sheet is provided.

ATTERBERG LIMITS

SAMPLE Nº __________ PROJECT ____________________ DATE ____________

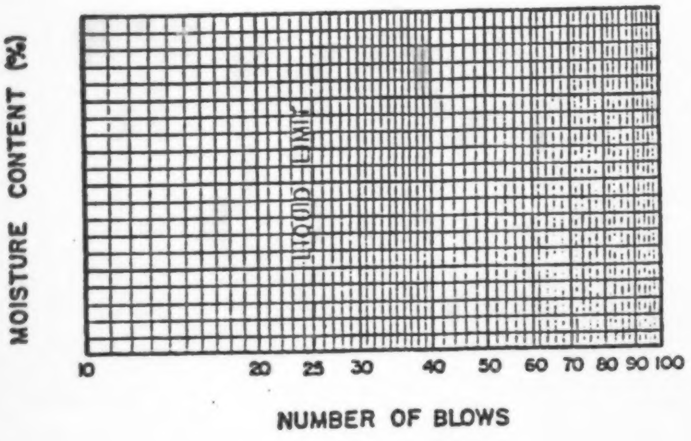
SOURCE OF SAMPLE ____

SUMMARY

NATURAL WATER CONTENT	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	SHRINKAGE LIMIT

PLASTIC LIMIT				NATURAL WATER CONTENT		
DETERMINATION Nº	1	2	3	1	2	3
CONTAINER Nº						
CONTAINER + WET SOIL						
CONTAINER + DRY SOIL						
WEIGHT OF WATER						
CONTAINER + DRY SOIL						
WEIGHT OF CONTAINER						
WEIGHT OF DRY SOIL						
PERCENT WATER						

LIQUID LIMIT						
DETERMINATION Nº	1	2	3	4	5	6
NUMBER OF BLOWS						
CONTAINER Nº						
CONTAINER + WET SOIL						
CONTAINER + DRY SOIL						
WEIGHT OF WATER						
CONTAINER + DRY SOIL						
WEIGHT OF CONTAINER						
WEIGHT OF DRY SOIL						
PERCENT WATER						



TESTED BY ______________________________________

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Standard Unconfined Compression

Principle of Test Method: This method uses a compression device to determine the unconfined compressive strength of a soil sample: that is the load per unit area at which the specimen fails in simple compression.

Test Method

(1) Apparatus: Compression device, sample ejector, deformation indicator, vernier caliper, timer, balance and oven.

(2) Procedure: An unidsturbed sample is secured and a specimen prepared as per the reference. An estimate of the failure strength is made based on experience with a similar material. The specimen is placed in compression by uniformly progressive loads at 30 second intervals till failure or 20% strain is reached. The results are plotted.

(3) Reference: ASTM D 2166.

Limitations: The method requires a laboratory environment, the securing of an undisturbed sample (as described by ASTM Method D 1587), considerable specimen preparation, calculations and considerable time.

Status of the Method: The method is the standard means for unconfined compressive strength determination. However because of its limitations it is not commonly used in process control (because of more efficient methods) but is widely used in acceptance testing.

Calibration Procedure: The deformation indicator must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the water content of the sample as well as the strain deformations at their respective loads. An example data sheet is provided.

UNCONFINED COMPRESSION TEST - DATA SHEET

Soil Description ______________________ Project ______________________

______________________ Laboratory ______________________

Boring No. ________ Surface Elev. ________ Sample No. ________ Sample Depth Interval ________

LL ________ % w ________ % PL ________ % Date Tested ________

Pocket Penetrometer, P.P. ________ tsf Specific Gravity, G_s ________ Dry Unit Weight, γ_d ________ pcf

Soil Specimen Measurements

Diameter: ________ in. Initial Area, A_o: ________ sf Initial Length, L_o: ________ in

Proving Ring Conversion Factor: ________ Corrected Area, $A_c = \dfrac{A_o}{1 - \varepsilon}$

WATER CONTENT

Specimen Location	Top	Middle	Bottom	Entire Remolded Sample
Container No.				
Wt. Cont. + Wet Soil(gms.)				
Wt. Cont. + Dry Soil(gms.)				
Wt. Container (gms.)				
Wt. Dry Soil(gms.)				
Wt. Water(gms.)				
Water Content(%)				

COMPRESSION TEST

Elapsed Time (Min.)	Load Dial Reading	Load (lbs.)	Vert. Dial (inches)	Axial Strain ε (%)	Corr. Area, A_c (sf)	Comp. Stress, S_c (psf)

Method No. 24

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Field Expedient Unconfined Compression

Principle of Test Method: This method uses a field expedient compression device to determine the unconfined compressive strength of a soil sample.

Test Method

(1) Apparatus: Sample selector, compression device, stress and deformation indicators, balance, oven and trimmer.

(2) Procedure: A sample is secured and prepared. An estimate of the sample's failure strength is made based on experience with a similar material. The specimen is then placed in compression by uniformly progressive loads till failure or a predetermined percent strain is achieved. The results are plotted.

(3) Reference: TM 5-530, 1971.

Limitations: The method involves a procedure virtually identical to that called for in the standard laboratory method. However the apparatus used in the field expedient method is less accurate, less care is given to sample preparation and the method itself is less accurate.

Status of the Method: The method lies between the standard laboratory method and the hand device methods in terms of accuracy and resources required. As the standard laboratory method is the accepted method for laboratory needs and the hand devices are sufficient for field testing. This method is not widely used.

Calibration Procedure: The stress and strain indicators must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the sample's water content as well as the stress and strain readings. No example data sheet is provided.

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Hand Penetrometer

Principle of Test Method: This method uses the hand penetrometer to determine the unconfined compressive strength of a soil sample.

Test Method

(1) Apparatus: Hand penetrometer with stress and strain indicators, trimming knife.

(2) Procedure: A sample is taken and trimmed by the hand penetrometer and a trimming knife. The test is then run with the device. One man can run the device and read the various stress and strain indicators. These values can be plotted and the unconfined compressive strength determined.

(3) Reference: Hvorslev, 1943.

Limitations: The sampling operation may cause a slight disturbance and decrease in strength of very brittle soils, a small downward deflection of soft soils, and a slight compaction of loose and partially saturated soils.

Status of the Method: The determination of cohesive soil consistency classification by this method is widely used as it is more accurate than the visual-manual method, and although it is less accurate than the standard laboratory method it is quite sufficient given the broad classifications for cohesive soil consistency.

Calibration Procedure: The stress and strain indicators must be zeroed at the beginning of the test.

Documentation of Test: Items to be recorded include the stress and strain readings during testing. An example data sheet is provided.

UNCONFINED COMPRESSION TEST

Soil Description ______________________ Project ______________________

______________________ Laboratory ______________________

Boring No. ________ Surface Elev. ________ Sample No. ________ Sample Depth Interval ________

LL ________ % w ________ % PL ________ % Date Tested ________

Pocket Penetrometer, P.P. ________ tsf Specific Gravity, G_s ________ Dry Unit Weight, γ_d ________ pcf

Axial Strain Rate: ______________________ inch/min.

Diagram of Failure:

Grain Size Distribution				
%Gr.	%C.S.	%F.S	% Silt	% Clay

Remarks: ______________________

____

Compressive Stress, Sc (psf)

Unconfined Compressive Strength

q_u = Max. Sc = ______________________ ps

Failure Axial Strain = ε_f = ________ %

Axial Strain, ε (%)

Parameter Measured: Cohesive Soil Consistency

Title of Test Method: Handheld Torvane

Principle of Test Method: This method uses a handheld torvane to determine the soil shear strength of the in situ soil.

Test Method

(1) Apparatus: Handheld torvane with gage.

(2) Procedure: The handheld torvane is pushed through the soil crust to the desired depth. A rotary motion is then applied to the handle. The gage values are read and the soil shear strength, values for cohesion and the internal angle of friction, and consistency classification can be determined.

(3) Reference: Lanz, 1968.

Limitations: The method is standardized and the values gained from the method can be correlated to the standard laboratory method for unconfined compressive strength. However the method is somewhat less accurate than others.

Status of the Method: The torvane is the most widely accepted of the shear vane devices. Since it yields in situ values rapidly it is widely used.

Calibration Procedure: The gage must be zeroed before testing.

Documentation of Test: Items to be recorded include the gage readings. No example data sheet is included.

Method No. 27

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: 25 Blow Standard Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test. This is the original Proctor test.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The specimen is prepared and placed in a mold. Most commonly the mold is the 4 inch mold. The soil is placed in three like layers. Each layer is compacted. Most commonly the compaction is 25 blows with a 5.5 pound hammer dropping 12 inches. Following compaction of all three layers the specimen is removed from the mold and trimmed. The mass of the sample is determined. This is divided by the volume of the mold and then the wet density of the sample, in pcf, is determined. The water content of the sample is then determined by oven drying. This entire procedure is repeated for at least four specimens. The four specimens' water contents should vary by about 1-1/2% between each sequential sample. The specimen water contents should bracket the estimated optimum moisture content. The values are plotted along with the "zero air voids curve." The optimum moisture content and maximum density of the sample can then be determined.

(3) Reference: ASTM D 698.

Limitations: This method requires a laboratory environment, the considerable time involved in sample drying and several hours to perform the test itself.

Status of the Method: This is the standard method. It is widely used. It is suited for the lesser compactive effort as might be applied to trench backfill. It may not be as suitable as the modified method for higher compactive efforts such as that which might be applied to a trench floor.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. An example data sheet is provided.

SOILS LABORATORY COMPACTION TESTS PROCTOR METHOD

Sample No.

SITE

HOLE

AREA

DEPTH

NUMBER OF BLOWS

PLASTIC LIMIT

SPECIFIC GRAVITY

DATE

RUN NO.	WEIGHT OF SAMPLE + CYLINDER KG.	WEIGHT OF CYLINDER KG.	WEIGHT OF SAMPLE KG.	WEIGHT OF SAMPLE LBS./CU. FT.	WATER ADDED GRAMS	WATCH GLASS NO.	WATER CONTENT % DRY WT.	REMARKS
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								

TESTED BY: DATE

COMPUTED BY: DATE

CYLINDER NO.

VOL. OF CYLINDER CU. FT.

UNIT WEIGHT FACTOR

CHECKED BY:

DATE

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: 25 Blow Modified Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The specimen is prepared and placed in a mold in three like layers. The mold most commonly used is the four inch mold. Each layer is compacted. The compaction used for the four inch mold is 25 blows with a 10 pound hammer dropping 18 inches. Following compaction of all three layers the specimen is removed from the mold and trimmed. The mass of the sample is determined. This is divided by the volume of the mold and then the wet density of the sample, in pcf, is determined. The water content of the sample is then determined by oven drying. The entire procedure is repeated for at least four specimens. The four specimens' water contents should vary sequentially by about 1-1/2 percent. The specimen water contents should bracket the estimated optimum moisture content. The values are plotted along with the "zero air voids curve." The optimum moisture content and maximum density of the sample can then be determined.

(3) Reference: ASTM D 1557.

Limitations: This method requires a laboratory environment, the considerable time involved in sample drying and several hours to perform the test itself.

Status of the Method: This is also a standard method. It is widely used. As it better represents greater compactive effort than does the original Proctor test, it is more suitable for process control testing for trench floors and the like.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Method No. 29

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Methods: Nonstandardized Proctor Compaction

Principle of Test Methods: These methods determine the optimum moisture content and the maximum density of a soil sample by kneading compaction, static compression or other devices.

Test Methods

(1) Apparatus: Molds, sieves, balance, drying oven, extruder, kneading device or static compression device.

(2) Procedure: The procedures are method specific. (See the references.) However the procedures are very similar to the standard laboratory methods. Only the nature of the compactive effort and the specifics of the mold size, etc., differ.

(3) Reference: Johnson and Sallberg, 1962; and Antrim, 1970.

Limitations: These methods require a laboratory environment, the considerable time involved in sample drying and several hours to perform the tests themselves.

Status of the Method: These are not standard laboratory methods. They were developed for use in special situations. They are used by several state highway departments. They are not widely used in the laboratory because of the preference for the standard methods or in the field because of the ease and sufficiency of other methods.

Calibration Procedure: See the references.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Rapid, One Point Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test and estimation, given one specimen test and its derived value.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure is essentially the same as that for the standard laboratory method. However, rather than running four or more (usually the number is five) specimens through the test and deriving a like number of points, only one test is run and one point is derived. The one point is at a water content estimated to be on the dry side of the optimum. From this point, and the well documented data on the soil, the optimum moisture content and maximum density can be determined.

(3) Reference: EM 1110-2-1911, 1977.

Limitations: This method depends upon good and well documented data on the local soils. The method also depends upon data which defines a relatively good line of optimums.

Status of the Method: For suitable soils this method provides a much more rapid means of process control. It is widely used. It is probable that this method could be sufficiently applied to the compaction of trench backfill.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Method No. 31

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Rapid, Two Point Proctor Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by an impact compaction test and estimation, given two specimen tests and their derived values.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure is essentially the same as that for the standard laboratory method. However, rather than running four or more (usually the number is five) specimens through the test and deriving a like number of points, only two tests are run and two points are derived. The first test is with a specimen estimated to be at the optimum moisture content or just on the dry side of the optimum. The second test is with a specimen 2 or 3 percentage points dry of the water content of the first specimen. From these points, and the well documented data on the soil, the optimum moisture content and maximum density can be determined.

(3) Reference: EM 1110-2-1911, 1977.

Limitations: This method depends upon good and well documented data on the local soils. The method also depends upon data which defines a relatively good line of optimums.

Status of the Method: In this method two curves are developed, as opposed to one curve as in the one point method, thus this method can be expected to yield a better estimated curve. As this method provides more accuracy than the one point method, it is perhaps even more applicable to trench backfill compaction process control.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Hilf's Rapid

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by the standard impact compaction test of three samples, the use of standardized forms, and an estimate of the optimum moisture content.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure utilizes the standard impact compaction test. Three samples are tested. The first sample is that at field moisture, a water content estimated to be on the dry side of optimum. The second and third samples are tested at water contents two and four percent more than the field moisture. The derived values are compared to standardized forms and plotted. Without determination of water content, the maximum density and difference of the field moisture from the optimum content can then be determined. This is done by connecting the plotted points, which bracket the optimum moisture content, and thus yield its value.

(3) Reference: Hilf, 1970.

Limitations: This method is only suitable for low plasticity cohesive soils.

Status of the Method: When applicable this method yields sufficient data in much less time than the standard impact tests. However, because it yields only an approximation of the optimum moisture content its applicability is limited.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Ohio Highway Department Nest of Curves

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by the standard impact compaction test yielding one point, and its placement on a nest of curves for like soils.

Test Method

(1) Apparatus: Molds, rammer, extruder, balance, drying oven, sieves, circular slide rule.

(2) Procedure: A single test is performed as per one of the standard impact compaction methods. The derived point is then matched to a nest of curves. For field expedience this nest of curves is often contained on a circular slide rule. The optimum moisture content and maximum density are then estimated from the appropriate curve.

(3) Reference: Ohio Highway Department, 1958.

Limitations: This method depends upon good and well documented data on the local soils.

Status of the Method: Where a nest of curves exists this method is a rapid means of determining the optimum moisture content and maximum density. It has proven to be sufficient in a widespread history of usage.

Calibration Procedure: The rammer must be calibrated before initial use and again after each 1,000 molds.

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Method No. 34

Parameter Measured: Water Content/Density/Compactive Effort

Title of Test Method: Harvard Miniature Compaction

Principle of Test Method: This method determines the optimum moisture content and the maximum density of a soil sample by a kneading compaction test with the Harvard Miniature device.

Test Method

(1) Apparatus: Molds, tamper, extruder, balance, drying oven, sieves.

(2) Procedure: The procedure utilizes different apparatus than does the standard impact compaction test. Also this procedure utilizes kneading as opposed to impact compaction. Other than that, with the exception of specifics, the procedures are quite similar. This procedure is readily adaptable to better represent the actual field compactive efforts to be achieved.

(3) Reference: Wilson, 1970.

Limitations: This method is suitable only for soils passing the No. 4 screen. Thus it is applicable for usage at a hazardous waste disposal facility.

Status of the Method: The method is small in terms of apparatus cost and size, simple, adaptable to duplicate the compactive effort achieved by larger equipment and ideal for field laboratory use. For better representing the actual field compactive efforts to be achieved the kneading action of the Harvard Miniature apparatus is superior to the impact action of the impact devices.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the mold volumes, specimen masses, and specimen water contents. No example data sheet is provided.

Method No. 35

Parameter Measured: Cohesionless Soil Relative Density

Title of Test Method: Standard Laboratory Maximum Density

Principle of Test Method: This method determines the maximum relative density of a cohesionless soil sample by the use of a vibratory table.

Test Method

(1) Apparatus: Vibratory table, molds, dial indicator, calibration bar, scale, other related equipment.

(2) Procedure: A soil sample is oven dried. The sample is thoroughly mixed. The sample is placed in a mold with a surcharge weight. The mold is vibrated for 8 minutes. The volume of the densified soil sample within the mold is determined. The sample is weighed. The maximum relative density can then be determined.

(3) Reference: ASTM D 2049.

Limitations: The method requires a vibratory table. This item is not often found on field sites.

Status of the Method: The method is the standard method and is widely used for laboratory purposes. The provision exists for a wet method in the reference.

Calibration Procedure: The exact mold volume must be determined and the dial must be zeroed before the test.

Documentation of Test: Items to be recorded include the mold volume and the dry weight of the sample. An example data sheet is provided.

RELATIVE DENSITY

MINIMUM AND MAXIMUM DENSITY DETERMINATIONS

DATE ____________________

PROJECT ____________________

BORING NO. ____________________ SAMPLE NO. ____________________

CLASSIFICATION		
MOLD NO.	MOLD DIAMETER, IN. =	WEIGHT OF MOLD, W_m, LB =
VOLUME OF MOLD, V_m, CU FT =	END AREA OF MOLD, A_m, SQ FT =	

MINIMUM DENSITY

TRIAL NO.			1	2	3	4
WEIGHT LB	MOLD (OR TARE) AND SOIL, DRY	W				
	MOLD (OR TARE)	W_m				
	SOIL, DRY	W_s				
MIN DRY DENSITY, LB/CU FT = W_s/V		γ_d				
MIN DRY DENSITY, AVERAGE			LB/CU FT			

MAXIMUM DENSITY

METHOD USED

TRIAL NO.			1	2	3	4
HEIGHT, IN.	LEFT DIAL READING	h_L				
	RIGHT DIAL READING	h_R				
	AVERAGE DIAL = $(h_L + h_R)/2$	h_{avg}				
	INITIAL DIAL READING	h_o				
	HEIGHT CHANGE = $h_o - h_{avg}$	Δh				
VOL CU FT	VOLUME CHANGE = $(\Delta h/12) \times A_m$	ΔV				
	VOLUME OF SOIL = $V_m - \Delta V$	V				
WEIGHT LB	MOLD (OR TARE) AND SOIL, DRY	W				
	MOLD (OR TARE)	W_m				
	SOIL, DRY	W_s				
MAX DRY DENSITY, LB/CU FT = W_s/V		γ_d				
MAX DRY DENSITY, AVERAGE			LB/CU FT			

REMARKS ____________________

TECHNICIAN ____________________ COMPUTED BY ____________________ CHECKED BY ____________________

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PLATE XII-1

Parameter Measured: Cohesionless Soil Relative Density

Title of Test Method: Standard Laboratory Minimum Density

Principle of Test Method: This method determines the minimum relative density of a cohesionless soil sample by the standard method.

Test Method

(1) Apparatus: Molds, pouring devices, 3/8 in. sieve, and straight edge.

(2) Procedure: A soil sample is oven dried. The soil is segregated into a +3/8 in. and a -3/8 in. fraction by passing through the sieve. Each fraction is carefully poured to overflowing into pre-measured molds. The excess soil is screed off. The soil fractions are weighed and the minimum relative density determined.

(3) Reference: ASTM D 2049.

Limitations: The method depends upon the technician's ability to carefully pour the segregated soil sample into the molds and his ability to scree off the excess with minimum effect to the soil in the molds.

Status of the Method: The method is the standard method and is widely used. It lends itself well to field site usage.

Calibration Procedure: The exact mold volume must be determined before the test.

Documentation of Test: Items to be recorded include the mold volumes and the soil fraction weights. No example data sheet is provided.

Parmater Measured: Cohesionless Soil Relative Density

Title of Test Method: Modified Providence

Principle of Test Method: This method determines the maximum relative density of a cohesionless soil sample by the use of a hammer.

Test Method

(1) Apparatus: Mold, dial indicator, hammer, balance.

(2) Procedure: A soil sample is oven dried and thoroughly mixed. It is placed in a mold and a surcharge weight equivalent to 1 psi is applied. The mold is struck uniformly by a hammer in the specified fashion till the dial reading changes less than 0.005 inches for any 25 blow cycle. The sample is then measured.

(3) Reference: EM 1110-2-1906, 1970.

Limitations: A nonuniform distribution of the hammer blows over the height and circumference of the mold may cause error in the determination of the maximum relative density.

Status of the Method: The method is not as accurate as the standard laboratory method. However, because no vibratory table is required and because the method's accuracy is sufficient for process control, the method is widely used at field sites.

Calibration Procedure: The exact mold volume must be determined and the dial must be zeroed before the test.

Documentation of Test: Items to be recorded include the mold volume and the dry weight of the sample after testing. No example data sheet is provided.

Method No. 38

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Bonded Seam Strength

Principle of Test Method: This method tests the seam strength of a specimen by placing it in tension and measuring its modulus of elasticity.

Test Method

(1) Apparatus: Grips, thickness gage, width-measuring devices, specimen cutter, extension indicators and a rate-of-jaw separation testing machine.

(2) Procedure: A specimen of a bonded seam is cut and measured and placed in the machine perpendicular to the center line. The specimen is then placed in tension. The same is done for a specimen of the sheet itself. The tensile modulus of elasticity for both are calculated. The bonded seam strength can then be calculated as a percentage of the sheet strength.

(3) Reference: ASTM D 3083.

Limitations: This method requires a qualified test conductor, the apparatus described and a "sheltered" environment to yield significant accuracy. A deficiency in any of these requirements would limit the validity of the method.

Status of the Method: This method is probably not applicable to all quality assurance programs for hazardous waste disposal facilities. The apparatus, "sheltered" environment and qualified test conductor may be too much for a small operation. The equipment needed is also expensive and another method might prove to be more economical. Modified methods, the results of which correlate to this standard method, have been developed and are proving acceptable. These modified methods do not require the "sheltered" environment or as elaborate apparatus.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading versus time and elongation versus time. No example data sheet is provided.

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Breaking Strength

Principle of Test Method: This method tests the breaking strength of specimens by placing them in tension in two transverse directions till they break.

Test Method

(1) Apparatus: Straining mechanism, clamps for holding specimen, and load and elongation recording mechanisms.

(2) Procedure: At least ten specimens of a bonded seam should be cut and measured (if one of the tests is invalid another specimen must be tested to yield a total of ten tests). The specimens are placed longitudinally in the clamps and strained till they break. Specimens should be strained till breakage in both the parallel and perpendicular to the seam directions. The average of five valid tests is the breaking strength of the seam in that direction.

(3) Reference: ASTM D 751.

Limitations: The specimens can tear or slip at the clamps.

Status of the Method: This method is probably not applicable to all quality assurance programs for hazardous waste disposal facilities. The ten or more specimens required are considerable. The equipment needed is relatively expensive yet very accurate. Electric power is required. However for a large operation the method may be applicable as it yields accurate, valid data in a short time. Modified methods, the results of which correlate to this standard method, have been developed and are proving acceptable. These modified methods do not require the "sheltered" environment or as elaborate equipment.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading versus time, elongation versus time, and loading at breakage. No example data sheet is provided.

Method No. 40

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Peel Adhesion

Principle of Test Method: This method tests the peel adhesion of a specimen by measuring the force it takes to peel apart a bonded seam.

Test Method

(1) Apparatus: A CRE or CRT-type, power driven, tension testing machine; or a frame and mandrels for the Static-Mass Method.

(2) Procedure: A specimen of a bonded seam is cut and measured. At one end of the specimen the parts are separated. The separated parts are attached to the machine. The tension on the separated parts is increased till failure. All forces and separations are carefully measured.

(3) Reference: ASTM D 413.

Limitations: A CRE or CRT-type machine requires power. A frame and mandrels set is inexpensive but is also uncommon to many construction site field testing facilities. Tearing of one or both of the separate parts of the specimen during loading is a hazard.

Status of the Method: Because of its ease and simplicity this test is applicable to a quality assurance program for a hazardous waste disposal facility. The frame and mandrels set are inexpensive. The test method does not require a "sheltered" environment beyond what most construction site field testing facilities provide.

Calibration Procedure: See the reference.

Documentation of Test: Items to be recorded include specimen dimensions, exact loading forces versus time and separations versus time. No example data sheet is provided.

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Air Lance

Principle of Test Method: This method tests the bond of a seam by detecting anomalies with a jet of compressed air.

Test Method

(1) Apparatus: A source of compressed air (40-60 psi), a wand pipe narrow tip nozzle (e.g. 3/16 in.).

(2) Procedure: One man walks the length of the bonded seam, pointing the nozzle and air jet at the edge of the top flap, within one inch of the same, with the nozzle parallel to the edge. A bubble will form under any unbonded edges. The results of such a bubble will be both audible and visual.

(3) Reference: N/A

Limitations: The method should be conducted with specimen testing (see test methods 38, 39 and 40) to assure field seam integrity and reliability. The method may not detect small anomalies.

Status of the Method: The method is applicable to a quality assurance program as a relatively rapid and rough determination of seam integrity. It should be conducted along with specimen testing. Its advantages over methods 42 and 43 are its ease, speed and economy. Its disadvantage is its rough detection capability. It will not detect pinholes. But where complete bonding is the critical determination, such as might be the case in an installed geomembrane used as part of a trench cover system, this method may be sufficient by itself.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include the detection and location, as well as marking of all anomalies. No example data sheet is provided.

Method No. 42

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Vacuum Box

Principle of Test Method: The method detects leaks in the seam by means of a vacuum.

Test Method

(1) Apparatus: Vacuum pump, power plant, inspection box, vacuum guage, soap, gasket.

(2) Procedure: The seam is lathered with soap to form a tight fit with the gasket. The inspection box is passed over the seam and it will detect any leaks to include those of pinhole size. The method tests seam integrity by detecting leaks. It does not test seam strength.

(3) Reference: Copywright by American Pipe & Steel Corporation.

Limitations: This method was developed for testing metal tanks and other similar containers. Because it is labor intensive, and because of the considerable time required, the method does not lend itself to expedient seam integrity testing. The length of a particular seam, the seam edges, the weight of the equipment, the relative labor intensity and the steep slopes of trench walls are all pontentially troublesome.

Status of the Method: This method is applicable to a quality assurance program for a hazardous waste disposal facility, especially where the permittee wants a great degree of confidence in the seam integrity and impermeability. All the equipment can be purchased for less than $1000. But as it requires a two man crew and covers 5 to 6 feet per minute it can be costly in labor costs and construction time. This method is the best for giving assurance in the seam integrity of any installed geomembrane. This method will detect leaks the others will not. This method should be the bottom line, the "last line of defense," test for any geomembrane usage where impermeability is critical. Often the labor intensity and time requirements of this method can be mitigated by using it in conjunction with the air lance method, conductivity method or an ultrasonic method. These latter three methods can locate larger anomalies rapidly. Thus the vacuum box will be left only small anomalies or pinholes to detect and its operation will be more continuous and thus less costly.

Calibration Procedure: N/A

Documentation of Test: Items to be recorded include leak detections, locations and markings. No example data sheet is provided.

Method No. 43

Parameter Measured: Geomembrane/Geotextile Seam Integrity

Title of Test Method: Conductivity

Principle of Test Method: This method electrically inspects the continuity of a seam by detecting changes in conductivity.

Test Method

(1) Apparatus: Battery, battery charger, battery tester, ground cable, coil spring electrodes and power pack.

(2) Procedure: The inspection electrode is passed over the seam. When anomalies in the seam are detected an audible signal is actuated by the instrument. The method does not test seam strength.

(3) Reference: Copywright by Tinker & Rasor.

Limitations: This method was developed for high voltage electrical inspection of pipeline coatings. Changes in the sub-seam soil water content can cause a change in the soil's dielectric constant and effect the readings. Thus uniform sub-seam soil nature and water content are desirable for the conduct of this method.

Status of the Method: This method is applicable to a quality assurance program for a hazardous waste disposal facility for it will detect seam leaks as well as bubbles, thin spots or foreign particles. It is relatively inexpensive and one man can operate it without special training. The high voltages involved should not present safety problems. Because of its wider use and acceptance this method was deemed to be currently more applicable for use at a hazardous waste disposal facility than the similar ultrasonic method.

Calibration Procedure: The instrument must be calibrated to the conductivity of the seam beforehand so that only anomalies are detected.

Documentation of Test: Items to be recorded include anomaly detections, locations and markings. No example data sheet is provided.